EPA-450/3-81-005a

Control Techniques for Particulate Emissions from Stationary Sources — Volume 1

Emission Standards and Engineering Division

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

September 1982

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402

This report has been reviewed by the Emission Standards and Engineering Division of the Office of Air Quality Planning and Standards, EPA, and approved for publication. Mention of trade names or commercial products is not intended to constitute endorsement or recommendation for use. Copies of this report are for sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, and the National Technical Information Services, 5285 Port Royal Road, Springfield, Virginia 22161.

CONTENTS

VOLUME 1

SUMMARY TABLE OF CONTENTS

VOLUME II

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF TABLES

LIST OF TABLES (continued)

SYMBOLS

Symbol	Definition
a	cross-sectional area
A	collection plate area of an electrostatic precipitator
A_w	wetted surface area
C	Cunningham correction factor
c	dust loading
d	diameter
d_d	drop diameter
d_f	fiber diameter
d_p	aerodynamic particle diameter
D	gas diffusivity
D_p	particle diffusivity
E_c	charging-field strength
E_p	precipitation field strength
g	acceleration of gravity
h	height
H_d	liquid holdup
K_p	inertia parameter
K_{pt}	inertia parameter at throat velocity
K_2	resistance coefficient of dust cake
l	bed depth
n	number of plates or stages
N_{RE}	Reynolds number

Symbol	Definition
p	total pressure
p_s	static pressure
p_c	corona power
P_t	penetration
q	particle charge
Q_l	liquid throughput
Q_g	gas throughput
r_d	drop radius
r_h	radius of hole
T	absolute temperature
t	time
t_R	residence time
v_g	gas velocity
v_p	pickup velocity
α	solid fraction in fiber bed
Δ_{ps}	static pressure change
η	efficiency
μ	gas viscosity
μ_L	liquid viscosity
ρ_g	gas density
ρ_L	liquid density
ρ_p	particle density
ρ_B	bulk resistivity
ρ_I	in-situ resistivity
ε	porosity
ω_e	migration velocity

CONVERSION FACTORS

1 meter (m) = 3.281 ft

1 meter (m) = 3.937×10^{1} in.

1 meter^2 (m^2) = 1.076×10^{1} ft^2

1 meter^3 (m^3) = 1.308 yd^3

1 meter^3 (m^3) = 3.532×10^{1} ft^3

1 meter/second (m/s) = 196.8 ft/min

1 meter/second (m/s) = 3.281 ft/s

1 meter^3/second (m^3/s) = 2.119×10^{3} ft^3/min

1 meter^3/second (m^3/s) = 1.585×10^{5} gal (U.S. liquid)/min

1 meter^3/second (m^3/s) = 2.282×10^{7} gal (U.S. liquid)/day

1 kilogram (kg) = 2.205 lb

1 kilogram (kg) = 1.102×10^{-3} short tons (2000 lb)

1 kilogram/meter^3 (kg/m^3) = 1.284×10^{-2} lb/ft^3

1 kilogram/meter^3 (kg/m^3) = 8.98×10^{1} grains/ft^3

1 joule (J) = 9.479×10^{-4} Btu (mean)

1 joule (J) = 2.778×10^{-7} kWh

1 watt (W) = 1.340×10^{-3} hp

1 pascal (Pa) = 1.45×10^{-4} $lb_f/in.^2$ (psi)

1 pascal (Pa) = 4.019×10^{-3} in. H_2O

1 pascal second (Pa-s) = 0.672 lb/ft^2-s

1 kilopascal (kPa) = 4.019 in. H_2O

GLOSSARY

ABSORPTION.[1] Transfer of molecules from the bulk of the gas to a liquid surface followed by diffusion to the bulk of the liquid.

ADIABATIC SATURATION.[1] A process by means of which an air or gas stream is saturated with water vapor without adding or subtracting heat from the system.

AERODYNAMIC DIAMETER. The diameter of a unit density sphere having the same aerodynamic properties as an actual particle.

AEROSOL. A dispersion of solid or liquid particles of microscopic size.

AGGLOMERATION. The combination of smaller particles due to collisions.

AIR, DRY. Air containing no water vapor.

AIR-TO-CLOTH RATIO (A/C). The volumetric rate or capacity of a fabric filter; the volume of air (gas) cubic meter per minute, per square meter of filter medium (fabric).

ATOMIZATION. The reduction of liquid to a fine spray.

BACK CORONA. Localized electrical breakdown of a dust layer, producing positive ions, which degrade or neutralize the intended charging process.

BAROMETRIC SEAL.[1] A column of liquid used to hydraulically seal a scrubber, or any component thereof, from atmosphere or other part of the system.

BLAST GATE.[2] A sliding plate installed in a supply or exhaust duct at right angles to the duct for the purpose of regulating air flow.

BLINDING (BLINDED).[2] The loading, or accumulation, of filter cake to the point where capacity rate is diminished.

BURNER.[1] A device for the introduction of fuel and air into a furnace at the desired velocities, turbulence, and concentration to establish and maintain proper ignition and combustion of the fuel.

CASCADE IMPACTOR. A particle-sizing device in which progressively increasing inertial forces are used to separate progressively smaller particle sizes.

CHEVRON MIST ELIMINATOR.[1] Series of diagonal baffles installed in a gas stream, designed to separate fine droplets of liquid from the gas by means of inertial impaction on the surfaces of the baffles.

COCURRENT. Flow of scrubbing liquid in the same direction as the gas stream.

COLLECTION EFFICIENCY.[1] The ratio of the weight of pollutant collected to the total weight of pollutant entering the collector.

CONDENSATION.[1] The physical process of converting a substance from the gaseous phase to the liquid or solid phase via the removal of heat, the application of pressure, or both.

CONTACT CHARGING. Charging of particles by contacting them and then releasing them from a charged surface.

CORONA CURRENT. Measure of the current flow from the transformer to its electrical section in an electrostatic precipitator (ESP).

COUNT.[2] The number of warp yarns (ends) and filling yarns (picks) per inch. Also called thread count.

CROSSFLOW. Flow of scrubbing liquid normal to the gas stream.

CROWFOOT SATIN.[2] A 3/1 broken twill arranged 2 threads right, then 2 threads left. Also called 4 shaft satin, or broken crow weave.

CUNNINGHAM FACTOR. A correction factor to account for slippage of fine particles moving through a discontinuous gaseous medium.

CURRENT DENSITY. Corona current level per unit area of collection surface of an electrostatic precipitator (current per plate).

CYCLONE. A device in which the velocity of an inlet gas stream is transformed into a confined vortex from which inertial forces tend to drive particles to the wall.

DAMPER.[2] An adjustable plate installed in a duct to regulate gas flow.

DEHUMIDIFY.[1] Reduction of water vapor content of a gas stream.

DEMISTER. A mechanical device used to remove entrained water droplets from a scrubbed gas stream.

DENIER.[2] The number, in grams, of a quantity of yarn, measuring 9000 meters in length. Example: A 200-denier yarn measuring 9000 meters weighs 200 grams. A 200/80-yarn indicates a 200-denier yarn composed of 80 filaments. Usually used to describe continuous multifilament yarns of silk, rayon, Orlon, Dacron, Dynel, Nylon, and similar materials.

DENSITY.[2] The ratio of the mass of a specimen of a substance to the volume of the specimen. The mass of a unit volume of a substance.

DIELECTRIC STRENGTH. The maximum potential gradient that may exist in a material without the occurrence of electrical breakdown.

DIFFUSION (AEROSOL). Random motion of particles caused by repeated collisions of gas molecules.

DIFFUSION (LIQUID).[1] The spontaneous intermingling of miscible fluids placed in mutual contact, and accomplished without the aid of mechanical mixing.

DIFFUSION CHARGING. Process of transferring electrical charge to particles by random movement of electrons and ions; the effective charging mechanism for submicrometer-sized aerosols.

DIFFUSIOPHORESIS. Force acting on a particle, effecting movement due to a vapor condensation gradient, resultant of differences in molecular impacts on opposite sides of a particle.

DIMENSIONAL STABILITY.[2] Capability of fabric to retain finished length and width, under stress, in hot or moist atmosphere.

DRAFT.[1] A gas flow resulting from the pressure difference between the incinerator, or any component part, and the atmosphere, which moves the products of combustion from the incinerator to the atmosphere. (1) Natural draft: the negative pressure created by the difference in density between the hot flue gases and the atmosphere. (2) Induced draft: the negative pressure created by the vacuum action of a fan or blower between the incinerator and the stack. (3) Forced draft: the positive pressure created by the fan or blower, which supplies the primary or secondary air.

DRAG FORCE. Resistance of a viscous medium due to relative motion of a fluid and object.

DUST.[2] Solid particles less than 100 micrometers created by the attrition of larger particles.

DUST LOADING.[2] The weight of solid particulate suspended in an airstream (gas), usually expressed in terms of grains per cubic foot, grams per cubic meter, or pounds per thousand pounds of gas.

DUST PERMEABILITY.[2] The mass of dust (grains) per square foot of media divided by the resistance (pressure drop) in inches water gauge per unit of filtering velocity, feet per minute. Not to be compared with cloth permeability.

ELECTROSTATIC FIELD. The position-dependent electrostatic force per unit charge, made up of two components--one related to applied voltage and electrode geometry, the other related to space change due to the presence of electrons, ions, and charged particles.

ENTRAINMENT SEPARATOR (DEMISTER). That part of a gas scrubber designed to remove entrained liquid droplets from a gas stream by centrifugal action, by impingement on internal surfaces of the scrubber, or by a bed of packing, mesh, or baffles at or near the scrubber gas outlet.

ENTRY LOSS.[2] Loss in total pressure caused by air (gas) flowing into a duct or hood.

EXCESS AIR.[1] Air supplied for combustion in excess of that theoretically required for complete combustion; usually expressed as percentage of theoretical air (130% excess air).

FABRIC.[2] A planar structure produced by interlacing yarns, fibers, or filaments. (1) Knitted fabrics produced by interlooping strands of yarns, etc. (2) Woven fabrics are produced by interlacing strands at more or less right angles. (3) Bonded fabrics or a web of fibers held together with a cementing medium which does not form a continuous sheet of adhesive material. (4) Felted fabrics or structures built up by the interlacing action of the fibers themselves without spinning, weaving, or knitting.

FEEDSTOCK.[1] Starting material used in a process. Can be raw material or an intermediate product that will undergo additional processing.

FIELD CHARGING. Process of transferring electrical charge to particles induced by high electric field strengths in the interelectrode space; the effective charging mechanism for particles greater than 1 micrometer.

FIELD STRENGTH. A force field created by a large potential difference between surfaces of different polarity; measured by the potential difference divided by distance between surfaces.

FILAMENT.[2] A continuous fiber.

FILL.[2] Crosswise threads woven by loom.

FILL COUNT.[2] Number of fill threads per inch of cloth.

FILTER MEDIUM. The substrate support for the filter cake; the fabric on which the filter cake is built.

FILTER VELOCITY. The velocity at which the air (gas) passes through the filter medium, or the velocity of approach to the medium. The filter capacity rate.

FLY ASH. Finely divided particles of ash entrained in flue gases arising from the combustion of fuel. The particles of ash may contain unburned fuel and minerals.

FUGITIVE DUSTS. A type of particulate emission made airborne by forces of wind, man's activity, or both--such as construction sites, tilled land, or windstorms.[3]

FUGITIVE EMISSIONS. Particles generated by industrial or other activities which escape to the atmosphere not through primary exhaust systems but through openings such as windows, vents and doors, ill-fitting oven doors, or poorly-maintained equipment.[3]

FUGITIVE EMISSIONS. Industrial process such as emissions from a point, area, or line source other than a stack, flue, or control system. Emissions escape to the atmosphere from a defined industrial process flow stream because of leakage, materials charging/ handling, inadequate operational control, lack of reasonably available control technology, transfer, or storage.

FUME.[1] Fine solid particles predominately smaller than 1 micrometer in diameter suspended in a gas. Usually formed from high-temperature volatilization of metals or by chemical reaction.

GALVANIC SERIES.[1] A list of metals arranged according to their relative tendencies to corrode. When dissimilar metals are joined together in an electrolytic solution, the one closest to the "active" end of the galvanic series corrodes preferentially to the one closest to the "passive" end.

GRAVITY, SPECIFIC.[2] The ratio of the mass of a unit volume of a substance to the mass of the same volume of a standard substance at a standard temperature. Water is usually the standard substance. For gases, dry air at the same temperature and pressure as the gas is often the standard substance.

GRID.[1] A stationary support or retainer for a bed of packing in a packed bed scrubber.

HEADER.[1] A pipe used to supply and distribute liquid to downstream outlets.

HUMIDITY, ABSOLUTE.[2] The weight of water vapor carried by a unit weight of dry air or gas.

HUMIDITY, RELATIVE.[2] The ratio of the absolute humidity in a gas to the absolute humidity of a saturated gas at the same temperature.

HYDROPHILIC MATERIAL. Particulate matter that adsorbs moisture.

INERTIA. Momentum; tendency to remain in a fixed direction, proportional to mass and velocity.

INTERCEPTION. A type of aerosol collection related to impaction, in which an aerosol impacts the side of an obstacle because of reduced mobility across streamlines.

INTERELECTRODE SPACE. The space between the discharge electrode and the collection plate; the active particle-charging region in an electrostatic precipitator.

INTERSTICES.[2] The openings between the interlacings of the warp and filling yarns; the voids.

ION, GASEOUS. A gas molecule that loses or gains one or more electrons.

IONIZATION. Generation of free electrons that become attached to gas molecules, forming ions.

ISOKINETIC SAMPLING. Matching the gas velocity at the sampling probe entrance to the gas velocity of the localized gas stream to collect a representative particle size distribution.

LIQUOR.[1] A solution of dissolved substance in a liquid (as opposed to a slurry, in which the materials are insoluble).

LOG-NORMAL DISTRIBUTION. A series of points that can be defined by a geometric mean value and a geometric standard deviation.

MEAN FREE PATH. The average distance between successive collisions of gas molecules; related to molecular size and number per unit volume.

MIGRATION VELOCITY. The average drift velocity of charged particles normal to the direction of gas movement; also known as precipitation rate parameter, a measure of the efficiency of collected particles to the volume of gas treated and the area of the collection plate.

MOBILITY. A measure of response per unit force; the ease of motion relative to the magnitude of the force-inducing motion.

MONOFILAMENT.[2] A continuous fiber of sufficient size to serve as yarn in normal textile operations.

MULLEN BURST. The pressure necessary to rupture a secured fabric specimen.

MULTIFILAMENT (MULTIFIL).[2] A yarn bundle composed of a number of filaments.

NAPPING PROCESS.[2] A process to raise fiber of filament ends (for better coverage and more surface area), accomplished by passing the cloth over a large revolving cage or drum of small power-driven rolls covered with card clothing (similar to a wire brush).

NEEDLED FELT.[2] A felt made by the placement of loose fiber in a systematic alignment, with barbed needles moving up and down, pushing and pulling the fibers to form an interlocking of adjacent fibers.

NONWOVEN FELT. A felt made by needling, matting of fibers, or compression with a bonding agent for permanency.

OPACITY. Measure of the fraction of light attenuated by suspended particulate.

PARTICLE. Small discrete mass of solid or liquid matter.

PARTICLE SIZE. An expression for the size of liquid or solid particle.

PARTICULATE MATTER. As related to control technology, any material except uncombined water that exists as a solid or liquid in the atmosphere or in a gas stream as measured by a standard (reference) method at specified conditions. The standard method of measurement and the specified conditions should be implied in or included with the particulate matter definition.

PARTICULATE MATTER, ARTIFACT. Particulate matter formed by one or more chemical reactions within the sampling train.

PENETRATION. Fraction of suspended particulate that passes through a collection device.

PERMEABILITY, FABRIC. The capability of air (gas) to pass through a fabric. Measured on Frazier porosity meter or Gurley permeometer. Not to be confused with dust permeability.

PENTHOUSE (ESP).[1] Weatherproof gas-tight enclosure over the electrostatic precipitator that contains the high-voltage insulators.

pH.[1] A measure of acidity-alkalinity of a solution; determined by calculating the negative logarithm of the hydrogen ion concentration.

PLAIN WEAVE.[2] Each warp yarn passing alternately over each filling yarn. The simplest weave, 1/1 construction; also called taffeta weave.

PLATE AREA. The effective area of both sides of the collecting surfaces in an electrostatic precipitator.

POLYDISPERSITY. A particle size distribution consisting of different size particles.

PRESSURE, STATIC. The pressure exerted in all directions by a fluid; measured in a direction normal to the direction of flow.

PRESSURE, TOTAL. The algebraic sum of the velocity pressure and the static pressure.

PRESSURE, VELOCITY. The kinetic pressure in the direction of gas flow.

PRIMARY PARTICULATE MATTER. Particulate matter emitted directly into the air from identifiable sources.

PRIMARY STANDARD. The national primary ambient air quality standard which defines levels of air quality that are necessary to protect public health.

PRIME COAT (PRIMER).[1] A first coat of paint applied to inhibit corrosion or to improve adherence of the next coat.

QUENCH.[1] Cooling of hot gases by rapid evaporation of water.

RAPPER (ESP). Device for imparting acceleration of the collecting surface to dislodge the deposited particles.

RAPPER INSULATOR. A device that electrically isolates a rapper from the high-voltage system of an electrostatic precipitator, yet permits the transmission of mechanical forces.

REFRACTORY.[1] Ceramic material used for the lining of vessels, ducts, and pipe for protection from heat, abrasion, or corrosion; also used for insulation.

RESISTIVITY. The impedance offered to charge transfer across a dust layer; defined by the ratio of electric field intensity to the current per unit area passing through the dust layer.

REYNOLDS NUMBER, FLUID. A dimensionless quantity in fluids to describe the ratio of inertial to viscous forces.

REYNOLDS NUMBER, PARTICLE. A dimensionless quantity in aerosol science to describe the ratio of inertial to viscous forces relative to the particle.

SATEEN.[2] Cotton cloth made with a 4/1 satin weave, either as warp sateen or filling sateen.

SATURATED GAS.[1] A mixture of gas and vapor to which no additional vapor can be added, at specified conditions. Partial pressure of vapor is equal to vapor pressure of the liquid at the gas-vapor mixture temperature.

SATIN WEAVE.[2] A fabric usually characterized by smoothness and luster. Generally made warp face with a great many more ends than picks. The surface consists almost entirely of warp (or filling) floats in construction 4/1 to 7/1. The intersection points do not fall in regular lines, but are shifted regularly or irregularly.

SECONDARY PARTICULATE MATTER. Particulate matter formed in the atmosphere by physical and/or chemical gas-to-aerosol conversion mechanisms.

SECONDARY POLLUTANT. A pollutant not emitted into the air from a pollution source, but formed in the air from the reactions of primary pollutants (often photochemically).

SEEPAGE. The migration of particles through a freshly cleaned fabric.

SIZE DISTRIBUTION. Distribution of particles of different sizes within a matrix of aerosols; numbers of particles of specified sizes or size ranges, usually in micrometers.

SLURRY.[1] A mixture of liquid and finely divided insoluble solid materials.

SMOKE. Small gasborne particles resulting from imcomplete combustion; particles consist predominantly of carbon and other combustible material; present in sufficient quantity to be observable independently of other solids.

SNEAKAGE. Portion of a gas stream that bypasses the intended collection area in an electrostatic precipitator.

SOOT. An agglomeration of carbon particles impregnated with "tar," formed in the incomplete combustion of carbonaceous material.

SPECIFIC GRAVITY.[1] The ratio between the density of a substance at a given temperature and the density of water at 4°C.

SPRAY NOZZLE.[1] A device used for the controlled introduction of scrubbing liquid at predetermined rates, distribution patterns, pressures, and droplet sizes.

SPUN FABRIC.[2] Fabric woven from staple (spun) fiber; same as staple.

STAPLE FIBER.[2] Manmade fibers cut to specific length (1½ in., 2 ft, 2¼ in., etc.); natural fibers of a length characteristic of fiber, animal fibers being the longest.

STOKES NUMBER. Descriptive of the particle collection potential of a specific system; the ratio of particle-stopping distance to the distance a particle must travel to be captured.

STREAMLINE. The visualized path of a fluid in motion.

SUSPENDED PARTICULATE MATTER. Particulate matter in the ambient atmosphere, as determined by a specific reference method; material generally referred to as total suspended particulate (TSP); consists of particles within the size range of 100 to 0.1 micrometer in diameter.

TENSILE STRENGTH.[2] The capability of yarn or fabric to resist breaking by direct tension. Ultimate breaking strength.

TEMPERATURE, ABSOLUTE.[2] Temperature expressed in degrees above absolute zero.

TERMINAL SETTLING VELOCITY. The steady-state speed of a falling particle after the equilibration of gravitation, drag, and buoyant forces has occurred.

TRANSFORMER-RECTIFIER SETS. Electrical device used in electrostatic precipitators to rectify a.c. to d.c. and to transform low voltage to high voltage.

THREAD COUNT. The number of ends and picks per inch of a woven cloth.

TURBULENT FLOW. A type of flow in which the fluid passes in a nearly random, fluctuating motion.

TWILL WEAVE.[2] Warp yarns floating over or under at least two consecutive picks from lower to upper right, with the point of intersection moving one yarn either outward and upward or downward on succeeding picks, causing diagonal lines in the cloth.

VAPOR. The gaseous form of substances that are normally in the solid or liquid state and whose states can be changed either by increasing the pressure or by decreasing the temperature.

WARP.[2] Lengthwise threads in loom or cloth.

WARP COUNT.[2] Number of warp threads per inch of width.

WET/DRY LINE.[1] The interface of hot, dry particulate-laden gas and cooling or scrubbing liquid, at which an accumulation of solids can occur.

WOVEN FELT.[2] Predominantly a woven woolen fabric heavily fulled or shrunk, with the weave completely hidden by the entanglement of the woolen fibers.

GLOSSARY
REFERENCES

1. Industrial Gas Cleaning Institute. Wet Scrubber Terminology. Publication WS-1, July 1975.

2. Industrial Gas Cleaning Institute. Fundamentals of Fabric Collectors and Glossary of Terms. Publication F-2, August 1972.

3. PEDCo Environmental, Inc. Technical Guidance for Control of Industrial Process Fugitive Particulate Emission. EPA-450/3-77-010, March 1977.

SECTION 1

INTRODUCTION

This document is a revision of "Control Techniques for Particulate Air Pollutants,"[1] which was published in January 1969. Changes and advances in the technology of particulate control have made parts of the original document obsolete. This second edition contains up-to-date information on the emission reduction capabilities, costs, energy requirements, and environmental impact of available control techniques, as required in Section 108(b) of the Clean Air Act of 1977.

As in the first edition, the control techniques are based on information from many technical fields. The methods and principles of operation of many of the techniques have been known for years, but much experience has been gained in their applications since 1969. The document also discusses techniques that are still in various stages of research and development, even though these new techniques are not yet available for general use.

Recent scientific data summarized in "Sulfur Oxides-Suspended Particulate Air Quality Criteria Document" have led to increased concern about particles in the inhalable size range. This revision includes an expansion of information on control effectiveness as a function of particle size. Information on the conversion of gaseous pollutants to aerosols (secondary particulate matter) has also been incorporated. The revised document reflects increased interest in fugitive particulate emission sources. Information has been added on techniques to prevent and control these emissions.

The document is issued as two volumes. Volume 1 presents basic technical information on particulate emissions and control techniques; Volume 2 deals with control technology applied to major categories of pollutant-emitting sources. The volumes are intended as general references for technical personnel in regulatory agencies and in the private sector.

Because the document is a general summary, it should not be used as the basis for developing or enforcing control regulations.

Volume 1 has eight sections. Section 2 presents fundamentals of aerosol mechanics, trends in emissions and air quality, and sampling procedures. The definition of particle size is of special importance because of the differences among the definitions in the technical literature. Section 3 discusses the general ways in which particulate emissions can be minimized--that is, by energy source and fuel selection, by process selection and modification, and by exhaust gas cleaning.

Section 4 presents detailed information on exhaust gas cleaning techniques. The operating principles, control effectiveness, and maintenance requirements are summarized for each major category of techniques. Section 5 discusses fugitive dust and industrial process fugitive emissions. Most exhaust gas cleaning techniques concentrate particulate matter into a liquid or solid waste stream. Accordingly, Section 6 presents information on the environmental impact of these materials. This information is accompanied by an evaluation of energy requirements for particulate control techniques.

Section 7 discusses the cost of particulate control. All the costs are in first-quarter 1980 dollars, unless otherwise indicated. Section 8 presents the state of development of novel particulate control concepts.

Section 9 discusses the sources of specific particulate emissions and the technology generally used to control emissions from novel sources. Volume 2 consists entirely of Section 9, "Sources of Particulate Emissions and Control Techniques." The page numbers in Volume 2, therefore, go from page 1-2 (this page) to page 9.1-1, the first page of Section 9.

The data are given in metric units specified in the International System of Units (SI). Conversion factors are listed in the front of the report, as are important symbols.

REFERENCES

1. U.S. Department of Health, Education, and Welfare. National Air Pollution Control Administration. Control Techniques for Particulate Air Pollutants. AP-51, January 1969.

SECTION 2

BACKGROUND

This section provides background information relative to particulate emissions and how they are measured. The generation of particulate matter from stationary combustion sources, industrial processes, and fugitive emission sources is discussed, along with the secondary formation and transport of particulate matter. Sampling and analytical methods of evaluating particulate matter are also described.

2.1 TRENDS AND PROJECTIONS IN PARTICULATE EMISSIONS

Particulate matter is generated by a variety of physical and chemical mechanisms, and is emitted to the atmosphere from numerous sources, including combustion, industrial process, fugitive emission, and natural sources. Particulate matter is composed of finely dispersed liquids and solids, including soot; dust; organic substances; inorganic substances, such as sulfur compounds, metallic oxides, and salts; and other substances. The chemical composition of particulate matter varies with source characteristics, geographic area, and season of the year.

An estimated 12.4 teragrams (Tg) of particulate matter is emitted from manmade sources in the United States each year.[1,2] The major contributors are stationary fuel combustion sources and industrial processes, which contribute 39 and 42 percent, respectively. Transportation sources account for 9 percent of the total, and solid waste disposal and forest fires each account for approximately 4 percent of the total.[1,2]

2.1.1 Air Quality and Particulate Matter Emission Trends

In 1971, the U.S. Environmental Protection Agency (EPA), promulgated both primary (health-related) and secondary (welfare-related) National Ambient Air Quality Standards (NAAQS) for particulate matter. Air assessment in 1979 showed that 395 counties were classified as "nonattainment" (not having achieved the NAAQS) for particulate matter, the Nation's most commonly monitored pollutant.

Ambient particulate levels at a monitoring site may be viewed as the sum of particulate from traditional sources, nontraditional sources, natural sources, and transported particulate. Each of these source types may at times account for a significant portion of the measured particulate at a particular monitoring site.[3] In the 1970's, particulate emissions from traditional sources were estimated to have decreased 46 percent nationally. Dominant in this national trend were decreases in particulate emissions from industrial processes and from fuel combustion.

2.1.2 Projections for Future Control Programs and Emissions

Traditional sources are still the dominant cause of nonattainment in many urban areas with heavy industry; these sources may be contributing anywhere from 15 $\mu g/m^3$ in residential areas to over 60 $\mu g/m^3$ in industrial neighborhoods.[3] Nontraditional sources (e.g., reentrainment of road dust, fugitive dust emissions from construction and demolition operations, and dust from unpaved roads and parking lots) may contribute from 25 to 35 $\mu g/m^3$ to citywide particulate levels, and thus prevent some urban areas from attaining the standard.

Nonattainment of air quality standards is also caused by natural, transported, and secondary particulates. Natural particulates are not amenable to control. Nonurban sulfates and other secondary particulates, transported primary particulates (up to 30 $\mu g/m^3$ in densely populated metropolitan areas), and urban secondary particulates ($\leq$10 $\mu g/m^3$ formed from gaseous emissions within the urban area) can be controlled by regional and local planning and by control of gaseous pollutants.[3]

Annual variations in precipitation have affected the annual average particulate levels by as much as 20 $\mu g/m^3$. Although meteorology cannot be controlled, the meteorological variations with time and location must be considered in air quality analysis and planning.

New sources will be subject to New Source Performance Standards (NSPS) as NSPS are developed for various industries. The Clean Air Act requires that the EPA develop NSPS to prevent new air pollution problems by requiring the installation of the best available technology considering cost, health and environmental impact, and energy requirements during initial construction. Designed to allow industrial growth without undermining air quality management goals, NSPS are established at a national level so that control requirements for new sources are uniform and consistent, regardless of location.

The impact of NSPS on air quality will become more significant as new plants are constructed and as older sources are either modified or replaced. Before amendments to the Act were promulgated in 1977, a study was undertaken to estimate the potential emissions impact of the NSPS program. Particulate emissions from stationary sources in 1990 were predicted to be in excess of 15 Tg/yr if new sources were required to meet only the State standards. If six NSPS were set for particulate matter each year during the 1980's, the 1990 emissions were predicted to be considerably less than 10 Tg/yr.[4]

Attention is being given to particle size distribution to distinguish the fraction of particulate matter that is likely to be inhaled and to the chemical characterization of individual components. EPA has a network of National Air Monitoring Sites (NAMS) in major urban areas to measure both particle size and chemical composition. Monitoring at these sites provides particulate data for enough urban areas with populations greater than 50,000 to permit the continued characterization of national trends in particulate. Improvements in the characterization of particulate components help in the assessment of shifts in the nature of particulate matter and in the selection of appropriate control strategies. A continuing concern is that a net improvement in overall particulate levels could mask a shift in composition toward the smaller particles.

2.2 SOURCES OF SUSPENDED PARTICULATE MATTER

Particulate matter is emitted into the atmosphere from a variety of manmade and natural sources, and is sometimes formed in the atmosphere by conversion of natural and anthropogenic gaseous constituents into particulate. This section discusses the sources of particulate matter and the sources of gaseous precursors to particulate matter.

2.2.1 Natural Emission Sources

Particulate emissions from natural sources are estimated to exceed emissions from manmade sources on a worldwide basis.[3] In areas remote from urban population centers with concentrations of industrial and transportation facilities, natural particulate emissions are typically responsible for more than half of the average measurable levels. Figure 2-1 indicates the estimated average nonurban particulate levels in the continental United States by region and the estimated fractions of these levels that are attributable both to natural and to manmade sources, and to particulate transported into the region.[3]

The most important of the natural particulate sources are soil and rock debris, forest fires, volcanoes, and ocean salt spray. On land, wind-entrained dust from soil and rock debris is the largest direct source of particulate. Wind-entrained dust concentrations vary across the continent, and they vary according to weather conditions. For example, in the Great Plains region of the United States, wind erosion of soil is estimated to produce more particulate than other sources in the region, and also can lead to high dust concentrations over large areas. Although most duststorms occur in the spring, they can be a problem in other seasons. Rainfall and soil erosion of an area also influence the frequency and severity of duststorms.

The contributions of volcanoes and forest fires to particulate levels can vary greatly. During most years, emissions from volcanoes do not contribute a large proportion of the natural particulate emissions; but in episodes such as the eruption of Mount St. Helens, Washington, starting in May 1980, volcanic particulate is a major component of regional particulate levels. Although the contribution of forest fires cannot be accurately determined, forest fires are important to urban air quality because such fires are frequently adjacent to urban areas.[3]

Ocean salt spray, probably the largest particulate emission source, has a limited effect that extends only a short distance inland.

2.2.2 Manmade Sources of Particulate

Manmade sources contribute less to overall particulate levels on a nationwide basis than natural sources (Figure 2-1), but they are important

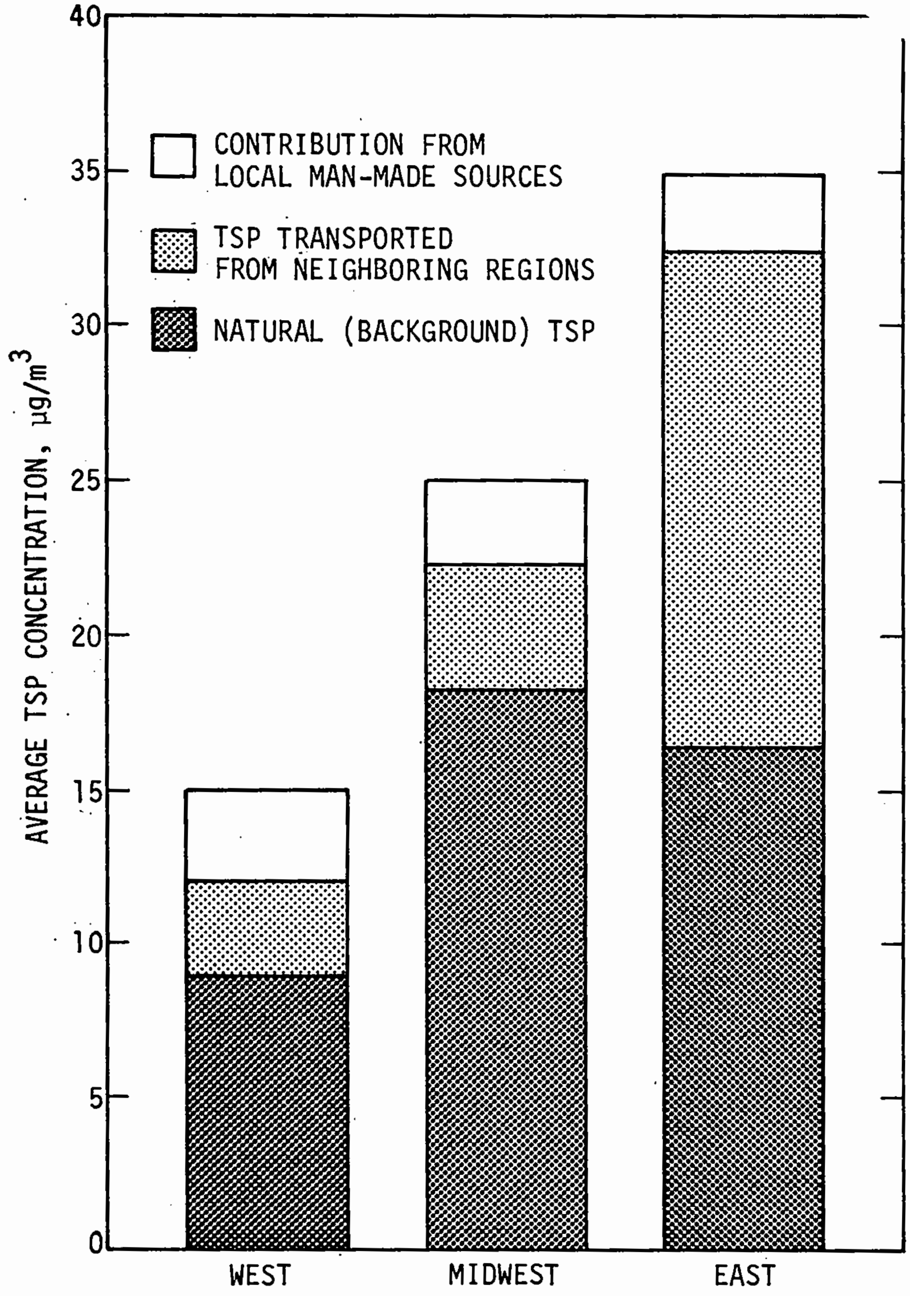


Figure 2-1. Estimated average contributions to nonurban TSP levels.[3]

with respect to air quality because they are usually concentrated near population centers where they are generated. Such anthropogenic particulate is the predominant component of particulate levels in many urban areas.[3] Manmade particulate sources are sometimes grouped into four broad categories: stationary fuel combustion, industrial processes, solid wastes disposal, and other significant sources. Table 2-1 summarizes the estimated contributions from each of these categories.[5]

The concepts of fugitive emissions and fugitive dust must be addressed in this discussion. Both of these terms refer to nonstack emissions of particulates. Fugitive emissions result when particulate from industrial operations finds its way to the atmosphere through building vents, windows, doors, and leaks in hooding and ductwork or when particulate is emitted from the open-air loading and transfer of materials. Fugitive dust, on the other hand, is an emission that becomes airborne by the forces of the wind in combination with man's activity. These emissions include windblown dust from construction sites, paved and unpaved roads, tilled farmlands, and mining operations. Fugitive dust, then, usually originates from nontraditional sources, but can originate from natural causes such as duststorms.

2.2.2.1 <u>Particulate Emissions From Stationary Combustion Sources</u>. Particulate matter emitted from stationary combustion sources represents approximately 35 to 50 percent of the total particulate generated in the United States by anthropogenic sources.[2,3] Combustion source particulate includes fly ash, soot, and sulfur oxide aerosols. Fly ash consists of inorganic material from the fuel, which is not destroyed during combustion and is subsequently entrained with the flue gas. Fly ash includes inorganic oxides, salts, and trace metals.[6] Soot consists of unburned carbon particles and polycyclic organic compounds formed under oxygen-deficient or low-temperature combustion conditions. Sulfur oxide aerosols are emitted in gaseous form from combustion sources that burn fuels containing sulfur. The sulfur oxides often condense into aerosols, which can contribute to overall particulate levels. Particulates formed from precursor gases after their emission into the atmosphere, such as sulfur oxide aerosols, are termed "secondary pollutants."

TABLE 2-1. ESTIMATED PARTICULATE EMISSIONS FROM MANMADE SOURCES, 1977[5]

Emission sources	Estimated emissions, Tg/yr
Stationary fuel combustion	
Utility boilers	3.4
Industrial boilers	1.2
Residential, commercial, institutional boilers	0.2
Subtotal	4.8
Industrial processes	
Chemicals and petroleum refining	0.3
Metals refining	1.3
Mineral products	2.7
Miscellaneous industrial processes	1.1
Subtotal	5.4
Solid waste disposal	___
Subtotal	0.4
Other significant sources	
Transportation	1.1
Forest fires and agricultural burning	0.6
Miscellaneous	0.1
Subtotal	1.8
Total emissions from all sources	12.4

Stationary combustion sources that emit particulate matter include utility boilers, industrial boilers, residential space heating, and commercial and industrial space heating. Utility boilers account for more than half of the emissions in this category, followed by industrial boilers (Table 2-1). The actual quantities of particulate matter emitted from a stationary combustion source are dependent on the size of the source, the efficiency of combustion, the efficiency of collection, and the amounts of sulfur and ash in the fuel. Fuels commonly used in stationary combustion sources include coal, oil, natural gas, and wood products. These fuels, ranging from low-grade, high-sulfur coals to clean-burning natural gas, vary considerably in their sulfur and ash content.

2.2.2.2 Emissions From Industrial Processes. Particulate emissions from industrial processes are formed primarily through the mechanisms of grinding, impaction, breakup of liquids, condensation, and chemical reaction. These emissions are characterized by a wide range of particle sizes and chemical compositions. The particles are chemically related to the processes from which they are generated. Thus, smelting and metallurgical operations, for instance, produce a large proportion of submicrometer-sized, condensed metallic fumes. Carbon particles and organic condensables such as tars are emitted from chemical operations related to the textile, petroleum/petrochemical, and plastics industries.

Grinding procedures such as those used in rock crushing, flour milling, and sanding operations produce predominantly large particles. High-temperature processes and those using volatile compounds generally produce aerosols of submicrometer size as a result of the condensation of vaporized solids or liquids. Such processes include pyrolysis, vaporization of lubricating or process oils, and metallurgical operations. Other sources that produce substantial amounts of submicrometer particulate emissions are lime kilns, pulp-mill recovery furnaces, and cement and asphalt plants.

Industrial-process fugitive emissions have the potential to contribute significant quantities to particulate burdens, especially in the vicinity of the source. With stack emission controls improving, the relative importance of fugitive emissions is growing. Because these emissions generally enter the atmosphere near ground level and at low velocities, their localized impact on air quality can be large. Major industries with potential fugitive emissions are listed in Table 2-2.[2,7]

2.2.2.3 Particulate Emissions from Solid Wastes Disposal. Incineration and open burning were traditionally the most common methods of solid waste disposal in urban areas. Under the pressure of more stringent pollution regulations, large municipal incinerators and industrial installations have been upgraded and controlled. With the continuing trend toward landfills, recycling, and the use of combustible rubbish as a fuel substitute, the decline of particulate emissions from solid waste disposal is expected to continue.[3]

2.2.2.4 Other Significant Particulate Sources. The remaining sources of particulates that could be considered significant may be grouped into two categories. One consists of sources created directly by some manmade action, such as emissions from vehicular exhausts, vehicular tire wear, and construction and demolition activities. The other category consists of re-entrainment sources, both natural and vehicle-related. Particulate matter can accumulate on city streets and other paved areas from unpaved roads and lots, truck spillage, sand and salt applied for snow control, and sediments washed over roadways during heavy rains. These particulates can become re-entrained by heavy winds and by vehicular traffic, and can produce an area-wide source of temporarily suspended particulate.[3]

2.2.3 Transported Particulate

As indicated in Figure 2-1, transported particulate represents a major portion of the average nonurban particulate levels in the continental United States. It is also evident that the importance of transported particulate increases as air masses move with the prevailing wind patterns from the Pacific Ocean across the continent. Transported particulate is both manmade and natural, and consists of both primary and secondary particulates. Movement of particulate from the source over a distance less than 100 km from the monitoring site is considered to be short-range transport; movement over more than 100 km is considered long-range transport.

The formation and transport of secondary particulate warrants special attention because the highest concentration of secondary particulate is in the size range of 0.01 to 1.0 μm.[8,9] Particulate in this size range is

TABLE 2-2. POTENTIAL INDUSTRIAL SOURCES OF FUGITIVE PARTICULATE EMISSIONS[2,7]

Food/agricultural industry	
	Alfalfa dehydrating
	Cotton ginning
	Grain terminals
	Grain processing
Metallurgical industry	
	Primary and secondary aluminum
	Metallurgical coke
	Primary copper
	Ferroalloys
	Iron
	Steel
	Primary and secondary lead
	Gray iron and steel foundries
	Primary and secondary zinc
	Secondary brass/bronze
Mineral products industries	
	Asphalt concrete
	Brick
	Castable refractories
	Cement
	Ceramics/clays
	Concrete batching
	Coal cleaning
	Glass
	Gypsum
	Lime
	Phosphate rock
	Stone quarrying
	Potash production
	Sand and gravel
	Diatomaceous earth
Forest products industry	
	Lumber and furniture

active in scattering light, and is also inhalable into the alveolar area of the lungs. The main ingredients in formation of secondary particulate are sunlight and gases such as sulfur oxides, ammonia, nitrogen oxides, ozone, water vapor, hydrocarbons, and oxygen. The sulfur oxides and nitrogen oxides are primary pollutants emitted in large quantities from combustion sources and internal combustion engines, but can also be precursors of secondary particulate matter. Secondary particulates arising from these precursors include nitrates such as nitric acid, sulfates such as ammonium sulfate and sulfuric acid, and organic particulates formed by the reactions of volatile organic compounds in the presence of sunlight.

2.3 MEASUREMENT OF PARTICULATE FROM STATIONARY POINT SOURCES

Particulate matter emitted from point sources may be measured to determine compliance with applicable emission limitations, to evaluate control equipment performance, or to establish emission factors. Many of the test methods, however, are subject to biases that may influence the validity of the results. The test procedures discussed here have been developed to minimize or eliminate these biases in obtaining representative samples.

2.3.1 Mass Concentration Measurement

The most precise method of determining the mass concentration of particulate matter in a gas stream is to collect the entire volume of gas and the particulate matter and to determine the mass concentration from this sample. This procedure, however, is feasible only with a few sources (with very low volumetric flow rates). Procedures for sampling small portions of a gas stream to obtain a representative sample of the total gas stream have been developed by various groups. Examples of these procedures are EPA Reference Methods 5 and 17, American Society for Testing and Materials (ASTM) Method D2928-71, and the American Society of Mechanical Engineers (ASME) Power Test Code 27. The predominant test procedure for characterization of particulate matter is EPA Reference Method 5, "Determination of Particulate Emissions from Stationary Sources," Appendix A, 40 CFR 60. Quality assurance checks in Method 5 and use of the method with EPA Methods 1, 2, 3, and 4 help ensure the accuracy of mass concentration determinations.

Method 5 is based on extractive filtration. Gas is extracted isokinetically; that is, the velocity of the gas entering the sampling nozzle is equal to the gas velocity passing by the nozzle at that sampling point. Extraction is done through a nozzle to an externally heated filter held at 120°±14°C. The particulate matter is captured in the sampling probe and on the filter, and then the filtered gases are passed through a series of impingers to remove moisture and other components before they pass through a dry gas meter. The sampling apparatus is shown as Figure 2-2. Isokinetic conditions must be maintained within ±10 percent of 100 percent for a valid test. In a gas stream with both large and small particles, sampling rates lower than 100 percent isokinetic can bias the sample toward larger particles, and can strongly bias the mass concentration calculations. The reverse is true with sampling rates above 100 percent isokinetic, in which the bias toward smaller particles would result in an apparent mass concentration that is lower than the actual emission rates.

Establishing isokinetic sampling rates depends on the characteristics of the individual sampling train and on determination of gas velocity, gas volumetric flow rate (EPA Method 2), gas molecular weight (EPA Method 3), and gas moisture content (EPA Method 4). The location and suitability of the sampling site and the location of the sampling points to provide a representative sample of the gas stream are performed according to the procedures of EPA Method 1. Thus the use of EPA Method 5 depends on the proper use of other EPA test methods, each of which affects whether the mass concentration data will be representative of the actual emissions from a stationary source. A brief review of these methods and their uses with Method 5 is necessary in evaluating test results.

The EPA Method 1 specifies criteria for selecting the sampling location and the location and number of sampling points. Emphasis is on locating the sampling locations away from flow disturbances such as fans, bends in ducts, and duct expansion or contraction points. The duct is divided into equal areas, and sampling points are at the centroid of each area. Generally, the closer a sampling location is to upstream or downstream disturbances, the more sampling points are needed to obtain a representative sample. The existence of cyclonic flow is checked because angular velocity patterns can lead to erroneous velocity determinations and to nonisokinetic sampling conditions, which can result in biased mass concentrations.

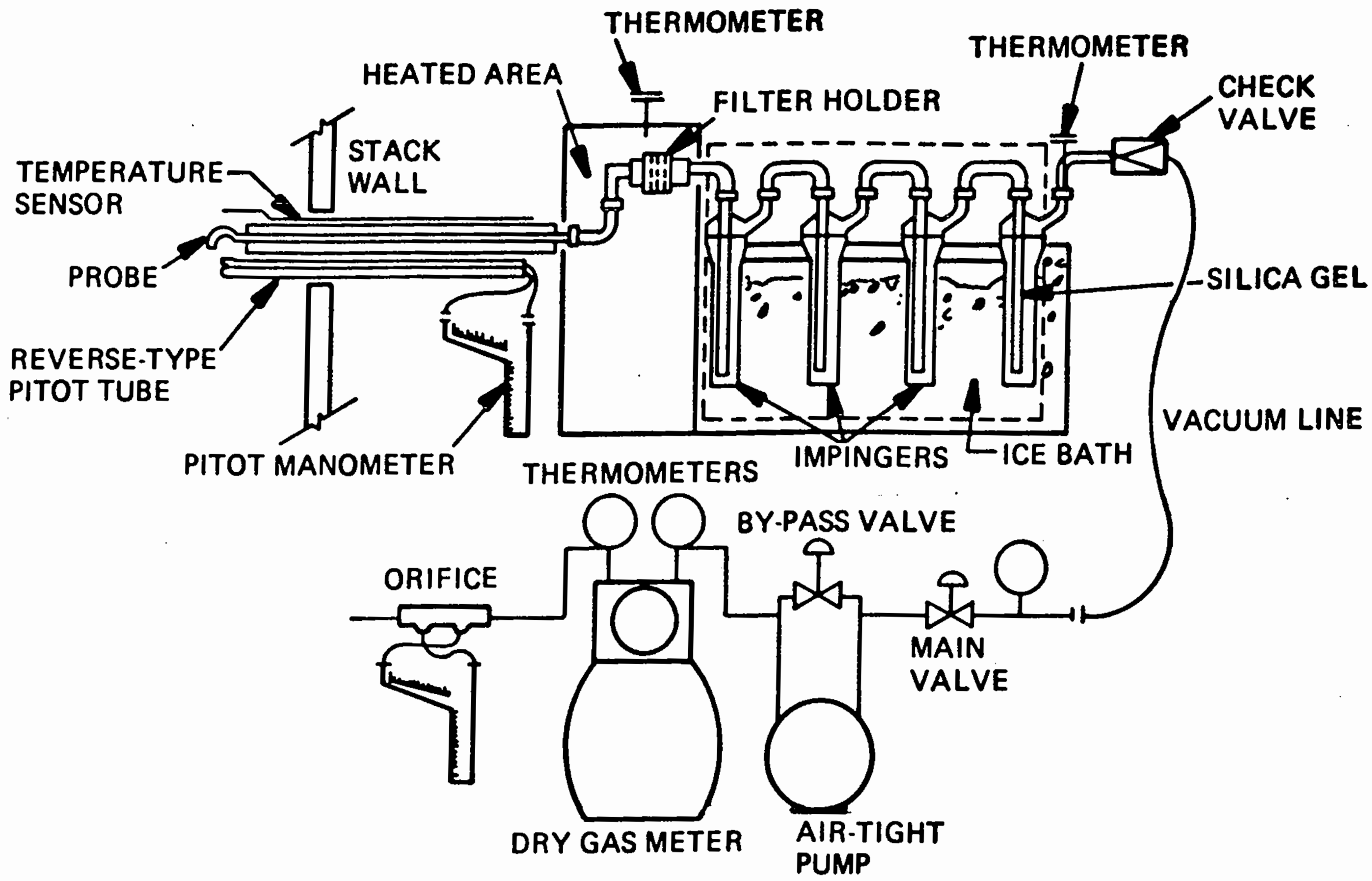


Figure 2-2. EPA Method 5 particulate sample apparatus.

The EPA Method 2 is used to determine local velocity pressures for establishing isokinetic sampling rate. Average gas velocity and volumetric flow rate may be calculated from a traverse of all sampling points. Typically, this method uses a Type S pitot tube because it yields a higher reading at a given velocity pressure than a standard pitot tube and because it is resistant to plugging. A Type S pitot tube is shown in Figure 2-3.

The EPA Method 3 is used to determine gas molecular weight, a value needed in determining gas velocity and volumetric flow rate. On combustion sources, an Orsat analysis for oxygen, carbon dioxide, and carbon monoxide is typically performed to assist in determining excess air and F-factor calculations for heat input and mass concentrations. Values obtained can aid in the determination of representative source-operating conditions and in the calculation of mass emissions in units specified by various standards.

The EPA Method 4 is used in the determination of moisture in stack gases. Although the moisture content is determined from the impinger catch of Method 5, a value for moisture content must be assumed for isokinetic flow calculations. For gas streams with low moisture content (e.g., 3 to 10 percent), the errors in isokinetics caused by assuming the wrong moisture content are relatively small. At high moisture content (greater than 10 percent), however, a small error in the estimated moisture can lead to sampling rates outside the acceptable range of 90 to 100 percent. For example, if the estimated moisture was 50 percent and the actual was 45 percent, the calculated isokinetic rate would be 111 percent. Method 4 may be used to aid in establishing a moisture content value for use in isokinetic sampling calculations. When high moisture content is encountered during particulate sampling, care should be taken to properly heat the probe and filter to avoid premature condensation.

For many sources, the amount of particulate matter captured on the filter is a function of temperature. In-stack filtration methods allow filtration to occur at approximately the same temperature as that of the stack gas. Thus, the amount of particulate captured should vary among sources, depending on the stack temperature and on the degree to which the particulate is temperature dependent. By use of an external filter of defined filtration characteristics at 120°±14°C, the captured particulate on the

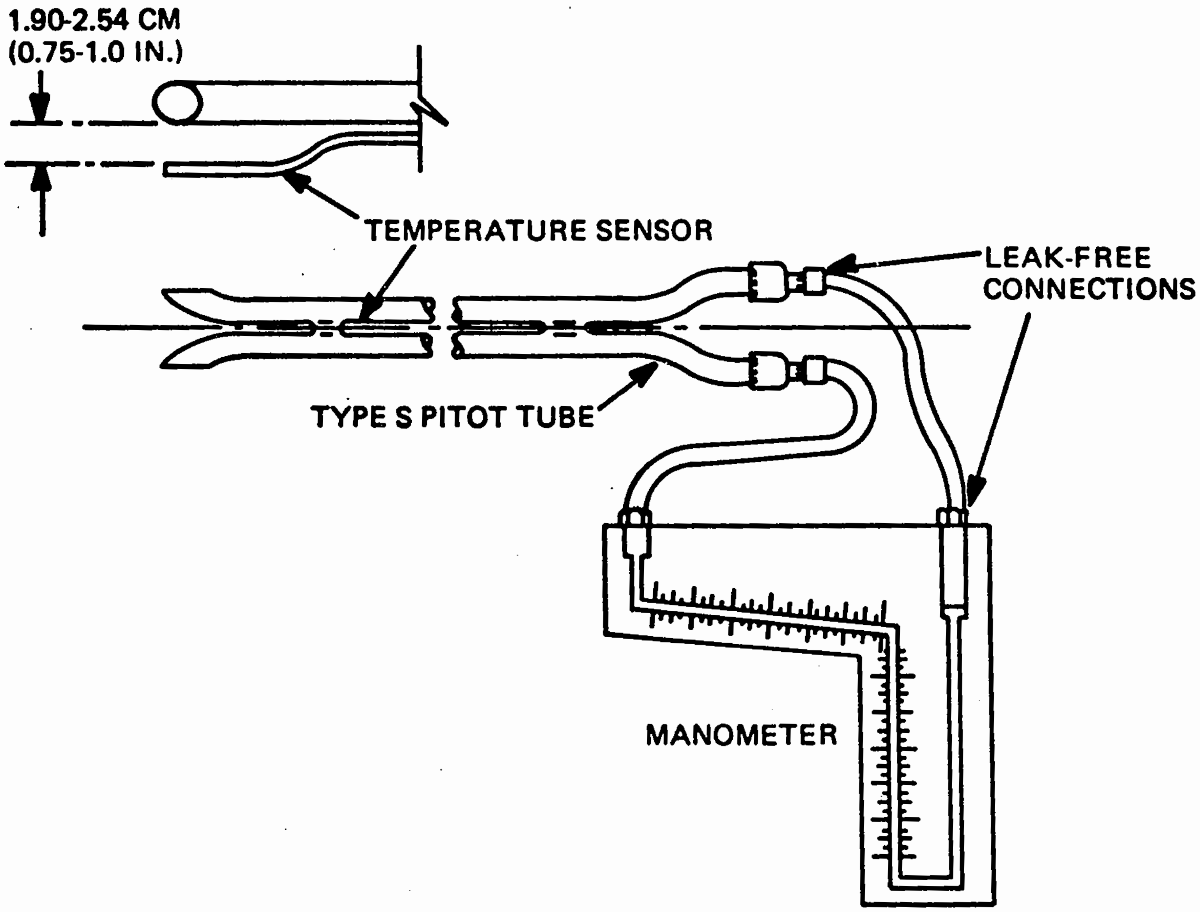


Figure 2-3. Type S pitot tube and manometer.

filter and in the heated probe is defined. This is the "front-half catch" of the Method 5 sampling train. Condensible particulate allowed to pass into the impingers along with water vapor is the "back-half catch." In certain jurisdictions, the back-half catch is included with the front-half catch as total particulate.

Significant biases may be introduced into the sampling results if the particulate is strongly temperature dependent and if the sample is not held at the proper temperature. Even though the filter holder is placed in a heated box within the 120°±14°C range, excessive heating or cooling in the sampling probe can affect the results. Of most concern is excessive probe heating, which can be caused either by a high probe-temperature setting or by a stack gas temperature higher than 120°C. Although the heated box may be at the proper temperature, the actual gas stream filtration temperature may be much higher. An excessive probe or filter temperature is of more concern in compliance tests, since the high temperature could tend to bias the mass concentration low.

Where there is no temperature dependency, EPA Method 17 uses an in-stack filter for particulate capture. As in Method 5, the sampling rate is isokinetic; EPA Methods 1, 2, 3, and 4 are used with the particulate sampling.

2.3.2 Particle Size Analysis

As part of the particulate emission characterization, a distribution of particulate sizes may be useful for determining control equipment parameters. The cascade inertial impactor is the device most commonly used for particulate sizing. The sampling train consists of the probe, a precutter such as a cyclone, and the cascade impactor.

The cascade inertial impactor technique provides a distribution of aerodynamic particle diameters. A cascade impactor usually has 5 to 10 stages of decreasing orifice diameters. The impactor is usually assembled to give an alternating pattern of orifice plates and collection plates. As the orifice size decreases, the gas velocity through each orifice increases. Larger particles cannot overcome the inertial force imparted to them through the orifice and thus impact the collector plate. Smaller particles have less inertia, and so the gas stream carries them to the next stage. The last stage is usually followed by a filter to capture the smallest particles that have escaped impaction. Gravimetric methods are used in analysis of each stage to determine particle size distribution, geometric mass median diameter, and geometric standard deviation. The results of cascade impactors are influenced by the deposition of particulate in the probe. For example, one test indicated that at a velocity of 15 m/s, 33 percent of the 10-μmA particles were collected in the probe.[10]

Cascade impactors are typically in situ (i.e., in-stack) devices used with isokinetic sampling rates. When samples are obtained in situ at the stack temperature, the particle size distribution should be representative of the actual particle size distribution in the duct. Failure to sample isokinetically results in the particle size distribution being biased and unrepresentative. A bias toward larger particle sizes occurs with underisokinetic sampling (velocity entering nozzle is lower than the localized gas velocity), and bias toward smaller sizes occurs with overisokinetic sampling.

Cascade impactors are provided in stages with nominal values for aerodynamic cut-size diameters. Calibration procedures are usually provided by the impactor manufacturer. Each impactor should be calibrated periodically to determine the actual value of the cut-size diameter for each stage.

Cascade impactors are susceptible to several problems. First, in gas streams with high particulate loadings, material may build up on the stages quickly and thus shorten the available testing period. Second, particle reentrainment and bounce can result in the particle size distribution being prejudiced toward smaller particles. Finally, fracturing of the larger particles at the impaction stage may lead to generation of fine particulate and to a consequent bias toward small particle sizes.

Although in situ cascade impactors are probably more common, extractive external cascade impactors are also in use. The particle size distributions obtained with these models are representative of the temperature of the impactor when there is temperature dependency of the particulate. Extractive cascade impactors may be used in observing temperature effects on particle size distribution and particle growth. The results from in situ and extractive cascade impactors should not be combined, because the sampling conditions are often different. Sample losses to the walls of the sampling probe are a potential problem with extractive samplers. The effects of over- and underisokinetic sampling are similar with both types of impactors.

Cyclones are used for in situ and extractive aerodynamic particle sizing, but not to the extent of cascade impactors. The aerosol sample enters the cyclone through a tangential inlet and follows a vortex flow pattern. Particles that cannot follow the gas streamlines move outward toward the cyclone wall and, depending on cyclone geometry, gas flow rate, and particle size, may reach the cyclone walls and be collected. By use of a series of cyclones of different geometric dimensions at a constant flow rate, particles can be removed according to size from a gas stream. The fractionating capability of cyclones is not predictable by theoretical means to the degree of accuracy possible with impactors. The advantages of cyclones over impactors is that large samples can be acquired and particle reentrainment is not so great.

Realtime particle sizing/counting has received minimal application to characterization of source emissions chiefly because the techniques require low mass concentrations. The instruments used in realtime analyses include optical devices, diffusion batteries, condensation nuclei counters, and electrical mobility analyzers.

Laboratory size distribution analysis of collected particulate samples is often performed instead of in situ procedures. The results of these methods must be interpreted with great caution, however, because the original flue gas particle size distribution is almost impossible to reconstruct under laboratory conditions. Particles or particle groups may be altered from their gas-stream state by additional agglomeration or particle breakup during sample collection. Size distribution results based on sedimentation and elutriation, centrifuging, sieving, and electronic counting are meaningful only when the effects of sample collection and redispersion are negligible or clearly known.

Microscopic analysis is regarded as the fundamental technique for counting and sizing particles. This procedure involves manual or computerized microscopic examination of a prepared slide containing a representative sample of the aerosol. Careful procedures must be followed in preparing the slide so that the aerosol sample is not altered from its in-stack state.

Although microscopic examination of particulate matter does not yield size information in terms of aerodynamic diameters, it can produce useful data on particle surface features, agglomeration, size, composition, and shape.

2.3.3 Analysis of Particulate Samples

2.3.3.1 General Considerations. Following the collection of a particulate sample at the sampling site, the sample must be analyzed to obtain a quantitative or qualitative measurement. Generally, the exposed filter or collection surface is returned to a laboratory for analysis. During this transfer, care must be exercised to avoid loss of fibers or particulate matter from the filter or the collection surface and to protect the sample from damage or conditions that may affect the analytical results. Special filter cartridges or filter holders are often used to safeguard the sample. Also transferred with the sample is an information record containing the site and sampler identification, the quality assurance data, and other pertinent information.

2.3.3.2 Artifact Mass. Artifact particulate matter can be formed on the surfaces of alkaline filter materials, such as glass fiber, by oxidation of acid gases in the sample air. Formation of artifact particulate results in an artificially high particulate measurement. This surface-limited effect usually occurs early in the sample period, and is a function of the filter pH value and the presence of acid gases. Although the artifacts usually account for only a small part of the collected particulate, the error can be significant when sampling periods are short or when the total amount of particulate matter collected is very small.

Reactions between various particulates collected on the filter are also possible. Although such reactions may not significantly affect gravimetric determinations, they may affect the chemical analysis of the sample.

2.3.3.3 Loss of Volatiles. Volatile particles collected on the filter may be totally or partially lost during subsequent sampling, during transport to a laboratory for analysis, or during storage before the postexposure weighing. Filters are normally analyzed as soon after collection as practical, but some loss of volatiles is inevitable.

2.3.3.4 Gravimetric Determination. Filters are conditioned and then weighed before and after exposure to determine the particulate weight as the net weight gain of the filter or the front-half of other collection surfaces. Mass concentration is determined directly by dividing the weight of the collected particulate by the total (standard) volume of air sampled. In addition to potential errors described earlier, errors are also possible in the weighing process.

2.3.4 Chemical Analysis and Analysis of Trace Elements

Most methods for trace element analysis of particulate material use spectroscopic detection. The detectors respond to the presence of only an element and provide no information about chemical compounds. Most methods do not indicate the oxidation state of the element.

2.3.4.1 Atomic Absorption Spectrometry. Atomic absorption spectrometry[11] is widely used for quantitative elemental analysis of airborne particles. It usually involves an acid extraction and excitation of the solution by a flame. Light with a wavelength characteristic of the one element of interest traverses the flame. The amount of light absorbed is related to the quantity of the element present.

Individual elements must be determined sequentially. Thus, although any element can be determined for which a lamp is available to produce the characteristic light, particulate samples are often large enough to allow only half a dozen determinations. Moreover, some trace elements present in the particles (including antimony and arsenic) may require the application of special methods.

Atomic absorption is subject to significant interferences and can lead to substantial errors. If recognized, these errors generally can be accounted for or eliminated to produce good quantitative analyses at the expense of additional effort on each sample. Despite its drawbacks, atomic absorption spectrometry is a useful method for elemental analysis of particulate.

2.3.4.2 Optical Emission Spectrometry. A variety of methods can be used to excite rather loosely bound electrons in elements and to observe characteristic emissions as de-excitation occurs. The wavelength is characteristic of the element, and the intensity is an indication of the quantity of the element present. The most desirable technique is argon plasma excitation of an acid extract of the particulate matter.[12]

Plasma spectrometry offers more advantages than atomic absorption since sample preparation and analysis rates are essentially equal. The spectrometry techniques, however, can simultaneously determine up to, perhaps, 50 elements with detection limits about the same as those of flame atomic absorption. Spectrometry is also more interference-free than atomic absorption, although not totally so.

2.3.4.3 Spark Source Mass Spectrometry. Spark source mass spectrometry[13] can analyze particulates separated from the filter and oxidized, or can be extracted with an acid. Spectral interferences are important, but generally can be overcome by use of a spectrometer with high resolution.

The precision can be about 30 percent (relative standard deviation) in careful analytical work. As with any multielement technique, its accuracy may depend on the element and on the matrix. The advantage of this technique is that one can simultaneously estimate the quantity of every nonvolatile element in the periodic table and do so with roughly equal sensitivity.

2.3.4.4 Neutron Activation Analysis. Neutron activation analysis[13,14] consists of a variety of distinct methods, all of which produce unstable nuclei that emit gamma radiation. The energy and intensity of the gamma rays are indicators of the element and its quantity. Instrumental thermal neutron activation analysis is most commonly used. In this approach, a nuclear reactor is used to produce unstable nuclei. Neutron activation analysis can simultaneously determine up to 25 elements in particulate samples. Another advantage is that particles can be analyzed as received directly on the filter surface.

2.3.4.5 X-Ray Fluorescence Spectrometry. X-Ray fluorescence spectrometry[13,15] involves excitation of tightly bound electrons and observation of the X-ray emission as de-excitation occurs. Excitation may be done by a variety of techniques, but use of an X-ray generator is the most common.

The technique may be either multielement (up to perhaps 30) energy dispersive detection or wavelength dispersive detection (up to perhaps 10 elements). Only elements with atomic numbers greater than that of magnesium can be analyzed. Particles can be analyzed nondestructively, directly on a filter; however, if samples are not thin and of uniform surface texture, certain corrections must be made. Interferences are common and must be considered, and adequate calibration can be a problem.

2.3.4.6 Electrochemical Methods. Electrochemical methods have been used to a limited extent to determine a small number of elements in particles. These methods include potentiometry with ion-selective electrodes, polarography, and anodic stripping voltammetry.[13] Electrochemical methods have few advantages for particle analysis aside from the low initial capital costs of equipment relative to that needed for other techniques.

2.3.4.7 Chemical Methods. Many wet chemical procedures constitute the classical methods used for trace element analysis of particulate. In general, a color-forming reagent is used, and the amount of an element is determined by the extent of color development. Probably the best known of these procedures is based on the use of dithiocarbazone (dithizone)[16] as the colorimetric reagent for lead. Wet chemical procedures are labor-intensive and slow, compared with spectral techniques, particularly since only one element can be determined at a time. Interferences can also be a problem.

2.3.4.8 Analysis of Organics. Procedures for estimating the total mass of benzene-extractable organic material in particulate matter have been used occasionally. A portion of the front-half catch is placed in a Soxhlet extractor and refluxed with benzene for several hours. Then the benzene is volatilized, and the mass of the residue is measured. This procedure presents problems because of special requirements for handling benzene.

Methods of identifying and determining individual organic species abound. These methods use different sequences of solvent extractions that separate groups of different organic species on the basis of solubility. Solutions are often subjected to chromatographic separation with mass spectral detection. For organic compounds that are volatile up to about 300°C, gas chromatography-mass spectrometry (GC-MS) can be used.[17] For organic species with lower volatility, liquid chromatography might be used. High-performance liquid chromatography (HPLC)[18] is typically used, but none of these procedures permits a high rate of analysis.

For analysis of one species of longstanding interest, benzo-a-pyrene (BaP), thin layer chromatography (TLC) with fluorescence detection is often used, and HPLC procedures have been proposed. The TLC procedure requires a cyclohexane extraction, spotting, and development of a TLC plate, with fluorescence detection. This procedure is more interference-free than some HPLC methods, and it has a higher production rate.[19]

REFERENCES

1. U.S. Environmental Protection Agency. National Air Pollutant Emissions Estimates, 1970-1978. EPA-450/4-80-002. Research Triangle Park, N.C. January 1980.

2. Adamson, L. F., and R. B. Bruce. Suspended Particulate Matter--A Report to Congress. U.S. Environmental Protection Agency, Environmental Criteria and Assessment Office. Research Triangle Park, N.C. October 1978.

3. U.S. Environmental Protection Agency. National Assessment of the Urban Particulate Problem, Vol. I. EPA-450/3-76-024. Research Triangle Park, N.C. July 1976.

4. U.S. Environmental Protection Agency. Priorities and Procedures for Development of Standards of Performance for New Stationary Sources of Atmospheric Emissions. EPA-450/3-76-020. Research Triangle Park, N.C. May 1976.

5. U.S. Environmental Protection Agency. National Air Quality Monitoring and Emissions Trends Report, 1977. EPA-450/2-78-052. Research Triangle Park, N.C. December 1978.

6. Faoro, R. B., and T. B. McMullen. National Trends in Trace Metals in Ambient Air, 1965-1974. U.S. Environmental Protection Agency. Research Triangle Park, N.C. EPA-450/1-77-003. February 1977.

7. U.S. Environmental Protection Agency. Technical Guidance for Control of Industrial Process Fugitive Particulate Emissions. EPA-450/3-77-010. Research Triangle Park, N.C. March 1977.

8. Whitby, K. T., R. B. Husar, and B. Y. H. Lia. The Aerosol Size Distribution of Los Angeles Smog. J. Aero. Atmos. Chem. (ed. G. H. Hidy). Academic Press, New York, 1971.

9. Clark, W. E., and K. T. Whitby. Concentration and Size Distribution Measurements of Atmospheric Aerosols and a Test of the Theory of Self-Preserving Size Distributions. J. Atmos. Sci., Vol. 24, 1967.

10. Smith, W. B., et al. Sampling Data Handling Methods for Inhalable Particulate Determination. Southern Research Institute. Birmingham, AL. March 1981.

11. Ahearn, A. I. Trace Analysis by Mass Spectrometry. Academic Press, New York, 1972.

12. Fassel, V. A. Quantitative Elemental Analyses by Plasma Emission Spectroscopy. Science, Vol. 202, 1978.

13. Morrison, G. H. Trace Analysis Physical Methods. Wiley Interscience, New York, 1965.

14. Lambert, J. P. F., and F. W. Wilshire. Neutron Activation Analysis for Simultaneous Determination of Trace Elements in Ambient Air Collected on Glass-Fiber Filters. Anal. Chem., Vol. 51, 1979.

15. Goold, R. W., C. S. Barrett, J. B. Newkirk, and C. O. Ruud. Advances in X-ray Analysis. Kendall/Hunt, Dubuque, Iowa, 1976.

16. Snell, F. D. Photometric and Fluorometric Methods of Analysis, Metals. Part I. John Wiley, New York, 1978.

17. McFadden, W. H. Techniques of Combined Gas Chromatography/Mass Spectrometry. John Wiley, New York, 1973.

18. Kirkland, J. J. Modern Practice of Liquid Chromatography. John Wiley, New York, 1971.

19. Swanson, D., et al. A Rapid Analytical Procedure for the Analysis of BaP in Environmental Samples. Trends Fluoresc., Vol. 1, 1978.

SECTION 3

ALTERNATIVE PARTICULATE CONTROL APPROACHES

Control of particulate emissions may be achieved either by prevention of particle generation or by collection of particles entrained in effluent gas streams. Prevention is preferable, both economically and environmentally; however, opportunities for this control approach are limited. A more commonly available strategy is process modification or optimization to improve particle collectibility. The costs of particulate control systems can be reduced, and their reliability can be improved by increasing the particle size, reducing the particulate mass loading, or reducing the variability of process operation; these measures can be combined to improve control. It is sometimes possible to modify particle characteristics to maximize collectibility.

These control measures represent alternatives to, or supplements to, installation of conventional particulate control systems. The following sections deal with these broad issues. Fuel switching is the most common and the most useful means to "prevent" particulate emissions. General approaches to process optimization illustrate possible benefits to subsequent control system performance. Finally, the control devices are briefly addressed. More detailed information on particulate control systems is in Section 4, and summaries of important processes are in Volume 2 of this document.

3.1 ENERGY SOURCE AND FUEL SELECTION

Energy substitution can be an effective and useful technique for reducing particulate emissions from stationary combustion sources. Substitution has special value in control of small and old sources, for which the cost of effective control devices might be expensive relative to the worth of the facility. Application of this approach is contingent on fuel availability and on the reduction in emissions to be achieved.

The particulate reduction potential may be estimated initially by comparison of published emission factors for various fuels. Because of site-specific combustion characteristics and highly variable fuel properties, such emission factors can provide only an estimate of the emission reduction potential. An emission factor analysis is presented in Table 3-1 for a pulverized-coal-fired power boiler.[1] The use of natural gas reduces emissions by 50 percent relative to No. 6 fuel oil and by 80 percent relative to coal firing with low-efficiency collection. Other clean fuels now available, such as distillate oil and refuse-derived fuels, could be included in a similar analysis. Because of the limited supplies of naturally clean fuels, this control option is severely restricted to use with only marginal boilers or furnaces where gas cleaning is not economically feasible.

TABLE 3-1. PARTICULATE EMISSION REDUCTION POTENTIAL OF VARIOUS ENERGY SOURCES

Energy source	Assumed particulate emission control, %	Particulate emission, ng/J ($lb/10^6$ Btu) of delivered energy
Natural gas	0	21 (0.048)[a]
No. 6 fuel oil	0	47 (0.108)[b]
Bituminous coal	98.0	140 (0.320)

[a]Based on an emission factor[1] of 15 $lb/10^6$ ft^3 for gas with a heating value of 37,300 kJ/m^3 and on an estimated conversion efficiency of 31.4 percent.

[b]Based on an emission factor[1] of 5 lb/1000 gal for oil to 0.3 percent sulfur content with a heating value of 42,000 kJ/liter and on an estimated conversion efficiency of 30.8 percent.

Development of synfuels will ultimately provide a more plentiful supply of clean fuels. Many synfuels, such as high-Btu gas and liquid solvent-refined coal, are believed to have combustion characteristics and particulate emission rates similar to those of natural gas. Many of these products could possibly be used without add-on particulate control devices. Other synfuels may have low ash content, but undergo moderate carbon losses that demand some degree of gas cleaning. Little information is yet available on particulate emission rates of synfuels.

Substitution of electric-powered devices for onsite power generation may provide relief from control requirements. This option again is most appropriate for small, economically marginal units. In this option, the particulate control requirement is simply transferred to the power generation facilities, most of which are equipped with high efficiency particulate control systems.

3.2 PROCESS OPTIMIZATION

Process optimization involves modifications of process feed materials, process unit functions, and process variables to eliminate or reduce particulate emissions.

Optimization of the process may reduce the volume of exhaust gases or alter the particle size distribution. A change in particle size distribution may allow a broader selection of abatement equipment, and emission standards may be achieved by application of equipment with lower energy consumption.

Selection of a process and implementation of process modifications may affect other process requirements, yields, or nonparticulate emissions. Therefore, in evaluation of process changes as means of particulate control, the total impact of the changes must be considered.

3.2.1 Modification of Process Feed Materials

The physical properties of feed materials, such as particle size, chemical composition, and moisture, may have significant effects on emissions from industrial processes. The effects vary from process to process, and the relationships must be developed on a process-by-process basis. In general, where heated air is used for drying, fine particles in the process feeds cause an increase in particulate emissions. Screening or cleaning of raw materials can reduce the particulate emissions per ton of product. Following are examples of process modifications that can reduce emissions resulting from the properties of feed materials.

3.2.1.1 Phosphate Rock Dryers. The screening or washing of phosphate rock before drying can reduce the weight of fine materials in the feedstock. These fines, referred to as phosphatic clay, have a substantial impact on the emission rate from uncontrolled dryers. The particulate loadings in dryer exhaust gases at several facilities has varied from 1.14×10^3 to 8.00×10^3 kg/m^3, depending on the condition of rock being processed. Removal of fine materials from the feed can permit operation of the control device at lower energy consumption and higher efficiency.

3.2.1.2 Secondary Lead and Copper Smelters. Operation of cupolas and blast furnaces at lead and copper smelters is affected by the composition and size of feed materials. The presence of fines in the charge reduces the furnace thermal efficiency, and requires the addition of excess coke. This results in higher combustion air pressure and flue gas volume. Fluctuation of the charge composition and the inability of the furnace to respond rapidly can cause severe swings in furnace temperature and exhaust gas volume; these changes can create positive pressures at charge doors, and generate fugitive emissions during charging. Control of the size and composition of the feed can reduce the capacity requirements for abatement equipment to contain and control the fugitive emissions.

3.2.1.3 Textile Fabric Coating. Curing of chemical coatings and finishes on textile substrates normally leads to the release of condensible hydrocarbon aerosols. The condensed organics can exhibit high opacity at relatively low particulate loading. The emissions normally result from chemicals incorporated into the fibers in previous processes. Removing these components prior to treatment has been shown to be effective in reducing particulate emissions from these processes. Application of latex coatings to textile fabrics that contain surfactants and plasticifiers has resulted in high opacities, and has necessitated the use of afterburners to control emissions. The need for afterburners can be reduced by modification of the chemical composition of the surfactants used in the coating system. In one instance, the surfactant was commercially available ammonium stearate. The emission was composed of oleic and palmitic acids, which had been introduced into the process as impurities in the ammonium stearate. When the stearate was converted to a purer form and the usage rate reduced, opacity of emissions dropped from 100 to 25 percent.

3.2.2 Elimination of Process Steps

The manufacture of products can require many individual process steps involving simple functions. The transfer of materials from one process to another can result in fugitive particulate losses. The loss of product can increase the cost of the finished marketed material, and also necessitates the application of pollution abatement devices. Often, a careful analysis of the number, order, and types of process steps can enable a company to reduce the number of emission points and to reduce emissions by eliminating repetitive and wasteful handling of materials.

The process changes many include installation of longer conveyors, transfer of product by pneumatic instead of open conveyors, or combination of process steps. In view of the energy required to transport materials and due to the cost of ductwork and abatement equipment, the elimination of even a single emission point can be cost effective.

3.2.3 Changes in Process Particle Characteristics

The particle size of the product being processed or handled can have a direct effect on the particulate emission rate. The wetting or agglomeration of materials can increase the effective particle size and the efficiency of control equipment. An example of change in particle characteristics that can reduce emissions is the transfer of wood fibers by using cyclones and pneumatic systems in the fiberboard industry. The uncontrolled emission of fibers from a cyclone handling 5000 kg/h of fiber can be as high as 300 kg/h. Prior to transfer, partial polymerization of the heat-setting resin that coats the fibers can reduce the emission to less than 5 kg/h.

3.3 EXHAUST GAS CLEANING

In a number of industrial processes, particulate emissions cannot be controlled satisfactorily by fuel switching or process optimization. In such processes, abatement of emissions to within the regulatory limits is usually achieved by adding exhaust gas cleaning devices. Among the many devices available for exhaust gas cleaning are cyclones, multicyclones, and other mechanical devices; shaker-type, reverse-air, and pulse-jet fabric filters; hot- and cold-side electrostatic precipitators; spray chamber, venturi, and packed-bed scrubbers; and incinerators. Each of these devices operates according to one or more of the basic physical or chemical principles discussed in Section 4.1, and each has distinctive advantages and disadvantages, as discussed in Sections 4.2 through 4.6.

Selection of a control device may involve a complex set of variables including regulatory limitations; the nature of the emissions source and its exhaust gases; the removal efficiency of each device; and long-term reliability, ease of maintenance, and total costs of installing and operating the device. Useful information is available in journals and other technical literature; in U.S. EPA publications; in publications of control device vendors and their representatives; through trade associations, professional organizations, and their technical committees; and through paid consultants. References 2 through 8 are examples of many publications which can provide initial direction in the search for information about exhaust gas cleaning.

3.3.1 Applicable Regulations

Air pollution control regulations vary with jurisdiction, and are subject to periodic revisions. Some regulations are promulgated at the Federal level: for example, New Source Performance Standards (NSPS),[9] National Emissions Standards for Hazardous Air Pollutants (NESHAPS),[10] National Ambient Air Quality Standards (NAAQS), and Prevention of Significant Deterioration (PSD). Other air emission regulations are promulgated at the State or local level: for example, those in State Implementation Plans (SIP).[11] Certain regulatory and enforcement functions related to air emissions are retained at the Federal level, but many enforcement functions have been delegated to the States. Some States, in turn, have delegated much of their authority to municipalities, counties, or regional air quality agencies.

The first step in determining regulatory requirements for a particular installation is to determine which local, State, and Federal agencies have promulgated applicable regulations. These agencies should be contacted for preliminary advice on the applicability and interpretation of current regulations. If analyses show that fuel switching and process optimization are not feasible, the technical and economic analyses of the various exhaust gas cleaning devices must be begun.

3.3.2 Source Characteristics

The characteristics of the source must be defined as completely as possible to select the most appropriate control device. Single value estimates of exhaust gas flow rates, temperatures, and particulate loadings usually are not necessarily sufficient for the reliable design of a control device.

characteristics of a source that are important to the design of a control device also include the process operating schedule, variability of fuel quality, the type of the raw materials, and the variability in process operations. These characteristics determine the variability of such exhaust gas parameters as temperature, moisture content, gas flow rate, particulate concentration, particulate size distribution, and concentrations of chemical constituents. A control device must be selected to provide the desired efficiency and reliability over the anticipated range of exhaust gas conditions. For example, the fabric in a fabric filter system must be chosen to withstand both the expected high and low temperature excursions and the typical or average temperature.

3.3.3 Control Device Design Limitations

Each type of device is limited in its capability to remove particulate from exhaust gases. In general, the particulate removal efficiency of each device is specific for each set of operating conditions. To provide the desired level of abatement, a device must be properly matched for the process conditions, the design must incorporate a sufficient factor of safety to handle unexpected contingencies, and the design limitations must not be exceeded because of increases in production rates after the device is installed.

3.3.3.1 Mechanical Collectors. Mechanical collectors are efficient for large particulate, but they cannot be expected to adequately remove fine particulate. Nor can they be expected to perform well on processes in which flow rates are extremely variable. A large increase in gas flow rates may increase the efficiency of mechanical collectors, but may also reduce their life by increasing abrasion. In contrast, a large reduction in gas flow rates will significantly decrease the efficiency.

3.3.3.2 Electrostatic Precipitators. Electrostatic precipitators must be sized to accommodate the expected gas flow rates, particulate concentrations, and fly ash resistivities. The specific collection area (SCA) must be great enough to handle the expected range of conditions. Exhaust gas loadings and fly ash resistivities must not be altered to such an extent that the SCA limitations of the precipitator are exceeded. In general, a properly designed electrostatic precipitator will collect nearly all particulate greater than 1 μmA in diameter, but particulate penetration increases as particle size decreases.

3.3.3.3 Fabric Filters. The principle limitations of fabric filters are the temperature limitations of available fabrics and the effects of fabric failures on the penetration of particulate. A properly sized fabric filter operating under dry conditions and within the temperature limitations of the fabric can provide extremely efficient collection over a wide range of particle sizes. Immediate replacement of broken filter bags is important in maintaining a low particulate emission rate.

3.3.3.4 Wet Scrubbers. A variety of wet scrubbers are available, each with certain performance limitations. Most wet scrubbers can operate efficiently in collecting large particulate (>2 μmA); some are also efficient for very small particulate (<0.2 μmA). Therefore, within many wet scrubbers there is a medium particle size "window" for which removal is less efficient. Particulate collection generally decreases as energy input decreases.

3.3.4 Control Device Reliability

The ultimate purpose of a normally efficient exhaust gas-cleaning device can be compromised if it suffers from frequent malfunctions. Malfunctions can reduce the performance of control equipment or cause periods of uncontrolled emissions; on occasion, plant production must be halted while the device is repaired. Malfunctions are caused by design deficiencies such as undersizing or omission of important ancilliary features or by improper operation and maintenance. Many of the common malfunction modes as well as design features and operating and maintenance procedures that can reduce the frequency and severity of malfunctions are described in Section 4.

3.3.5 Control Equipment Costs and Financial Assistance

A financial management decision regarding the purchase and operation of an exhaust gas-cleaning device should be aimed at selecting a device that will provide efficient reliable service over the desired service life at the lowest possible total annualized cost. An annualized cost determination must consider the amortization of control device investment, the direct and indirect costs of operating and maintaining the device, any credits for recovered particulate, and the effects of the device, if any, on production rates.[12,13,14] Tax relief or special financing schemes that could favorably affect the total annualized cost are sometimes available.[13,15]

3.3.5.1 Installed Costs of Control Equipment. The installed costs of control equipment include the costs of engineering and designing the equipment, the costs of materials of construction, cost of manufacturing, cost of transportation, and costs of labor and equipment during installation. Other costs associated with equipment installation may include the costs of production loss during installation and the costs of an initial stack test to verify performance of the device.

3.3.5.2 Direct and Indirect Operating Costs. Direct costs of operating a control device include the costs of utilities (e.g., electric power) to run the equipment and the costs of labor for operating the equipment. Other costs can include those for disposal of any collected particulate (if the collected particulate has economic value, this can be a negative cost or a net savings), the costs of periodic stack tests, and the costs of lost production due to control device malfunctions. A particulate control device may also have a positive or negative effect on production rates of some processes. Maintenance costs for a control device include the costs of replacement parts, of maintaining a spare parts inventory, and of labor associated with routine preventive maintenance or emergency maintenance.

Indirect operating costs include overhead, parts replacement, insurance, taxes, and amortization ("capital recovery") of the investment. Overhead is traditionally expressed as a percentage of operating and maintenance labor, whereas the other indirect costs are normally computed as a percentage of the control device investment.

REFERENCES

1. U.S. Environmental Protection Agency. Compilation of Air Pollution Emission Factors. AP-42, 1977.

2. U.S. Environmental Protection Agency. Office of Administration, Information Division. Need Air Pollution Information? Promotional Literature.

3. Industrial Gas Cleaning Institute. IGCI - Who We Are and What We Do. Promotional Literature. Stamford, Connecticut.

4. Catalog and Buyer's Guide - Pollution Equipment News. Rimbach Publishing, Inc., Waseca, Minnesota, Published annually.

5. Equipment Buyer's Guide Issue - Chemical Engineering. McGraw-Hill, New York, N.Y. Published annually.

6. Air Pollution Control Association. Journal of the Air Pollution Control Association. Pittsburgh, Pennsylvania. Published monthly.

7. Pollution Engineering. Technical Publishing. Barrington, Illinois, Published monthly.

8. Pollution Equipment News. Rimbach Publishing, Inc., Waseca, Minnesota. Published bimonthly.

9. U.S. Environmental Protection Agency. Standards of Performance for New Stationary Sources--A Compilation. EPA-340/1-77-015, October 1977.

10. U.S. Environmental Protection Agency. National Emissions Standards for Hazardous Air Pollutants--A Compilation as of April 1, 1978. EPA-340/1-78-008, 1978.

11. U.S. Environmental Protection Agency. Air Pollution Regulations in State Implementation Plans. EPA-450/3-78-050 through EPA 450/3-78-104, 56 documents, updated annually.

12. U.S. Environmental Protection Agency. Choosing Optimum Management Strategies--Pollution Control Systems. EPA-625/3-77-008, 1977.

13. U.S. Environmental Protection Agency. Choosing Optimum Financial Strategy for Pollution Control Investments. EPA-625/3-76-005, 1976.

14. Neveril, R. B. Capital and Operating Costs for Selected Air Pollution Control Systems. EPA-450/5-80-002, 1980.

15. U.S. Environmental Protection Agency. Major Financial Assistance Programs Available for Industrial Pollution Control Expenditures. EPA-340/1-77-023, 1977.

SECTION 4

PARTICULATE CONTROL SYSTEMS

Since "Control Techniques for Particulate Air Pollutants[1]" was originally published in 1969, there have been substantial advances in the capabilities of particulate matter removal devices. This section presents information on the many sophisticated and diverse control systems presently in commercial use. Each of the five major categories of systems is discussed in terms of types available, basic operating principles, design factors, and operation and maintenance considerations. Particle collection capability with respect to particle size is emphasized.

4.1 INTRODUCTION

Introductory information is presented on particle behavior and characteristics. Each particle control device takes advantage of one or more of the particle aerodynamic properties to remove particulate matter from the gas streams. Basic considerations in the application of particulate matter control devices as part of a system are also discussed.

4.1.1 Particle Characteristics and Behavior

It is helpful to understand basic principles of particle behavior in order to design a control device, to measure particulate matter concentrations, or to evaluate control device performance. More extensive information is available in aerosol physics texts such as references 2 through 10.

4.1.1.1 Particle Size and Shape. There are a wide variety of particle shapes. Spherical particles are usually generated in high temperature processes and in some cases the particle is partially or completely due to the condensation of vapors as the gas stream cooled. Small particles can link with other particles to yield a flocculant. Such flocculants tend to be fragile and can break apart during sampling or during passage through control devices. Fibrous particles result from the processing of certain natural biological and mineral materials. Asbestos is one type of fibrous particle. Depending on the chemical composition of the parent material, it is also possible to generate a flake-type aerosol. Mechanical attribution type processes such as grinding, sawing, and polishing can yield irregularity shaped particles. Such aerosols are generally larger than particles formed by condensation of vapors and other common types of aerosols.

Liquid aerosols are comprised almost exclusively of spherical particles or flocculants of spherical particles. In certain processes it is also possible to generate solid particles covered with an outer layer of liquid material. Solid aerosols can occur in any of the forms shown and in less common forms such as cubes and rods. Factors governing the ultimate shape of the particles include the chemical composition of the material and the characteristics of the process.

Particle size is the most important characteristic affecting behavior in gas streams, and it is a governing factor in the extent to which the particle scatters visible light and therefore contributes to plume opacity. The particle size range of interest to air pollution control studies is generally from 0.01 to 100 micrometers. Under the SI system of metric units, micrometer (μm) is the standard unit of particle size, and is 10^{-6} meters.

The many definitions of particle size are ultimately based on the size measurement method. For example, microscopic methods measure the projected area of particles. The projected area can be variously defined, depending on the means used to convert the dimensions of irregularly shaped and fibrous particles into a single "diameter" value. Likewise, sampling methods, such as cascade impactors can be used to measure particle size determined by observed behavior in a gas stream. The various measurement methods yield many size definitions that are not necessarily consistent with each other.

The most common definition for particulate control evaluation is the <u>aerodynamic particle diameter</u>, which is defined as the equivalent unit density sphere having the same aerodynamic characteristics as the actual particle. It is the product of the Stokes diameter times the square root of the product of particle density times the Cunningham slip correction factor:

$$d_p = d_{ps} (C\rho_p)^{0.5} \qquad \text{(Eq. 4.1-1)}$$

Throughout this document, particles sizes are given in terms of aerodynamic diameter (µmA) unless otherwise noted. The aerodynamic diameter is most closely related to the behavior of particles in control devices, and it is the "size" normally measured by stack sampling methods.

Each of the particle size measuring methods yields sets of data indicating the quantities of particulate in a number of size categories. These data can be compiled into a histogram, as shown in Figure 4.1-1 to graphically illustrate the aerosol distribution. The terms used to characterize the distributions of particles sizes are illustrated in Figures 4.1-2 and 4.1-3.

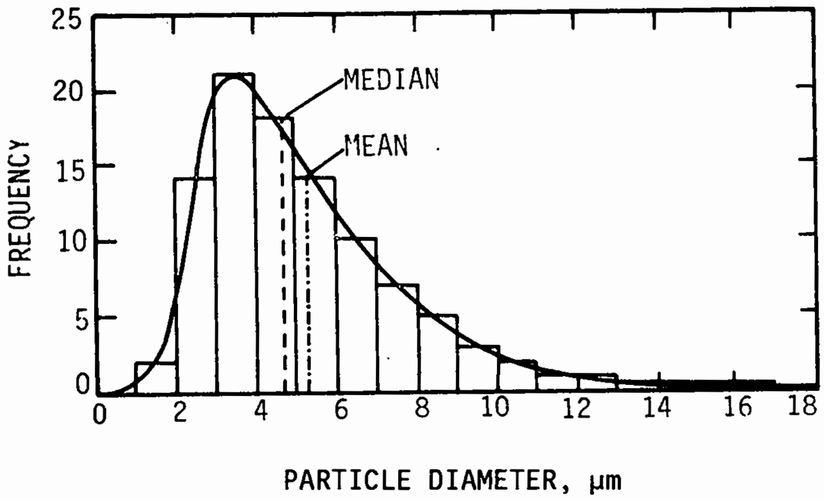


Figure 4.1-1. Aerosol distribution. (Reprinted from: Silverman, L., Billings, C.E., and First, M. W. Particle Size Analysis in Industrial Hygiene. Academic Press, 1971, p. 237.)

For example, the mean and the median are not equal for skewed distributions, as shown in Figure 4.1-1. The median particle size, by definition, divides the frequency distribution in half; 50 percent of the aerosol mass has particles with a larger diameter, and 50 percent has particles with a smaller diameter. A second measure of central tendency is the mean, which is simply the sum of all observations divided by the number of size categories used to construct the histogram; the mean is sensitive to the quantities of material at the extremes of the distribution, so relatively few large particles could shift the observed mean to larger levels.

For many industrial sources, the particle distribution approximates a lognormal distribution function. When the log of the particle diameter is plotted against the frequency of occurrence, a normal bell-shaped curve (shown in Figure 4.1-2) results, which is characterized by the geometric mean diameter--the sum of the logs of the observations divided by the number of size categories.

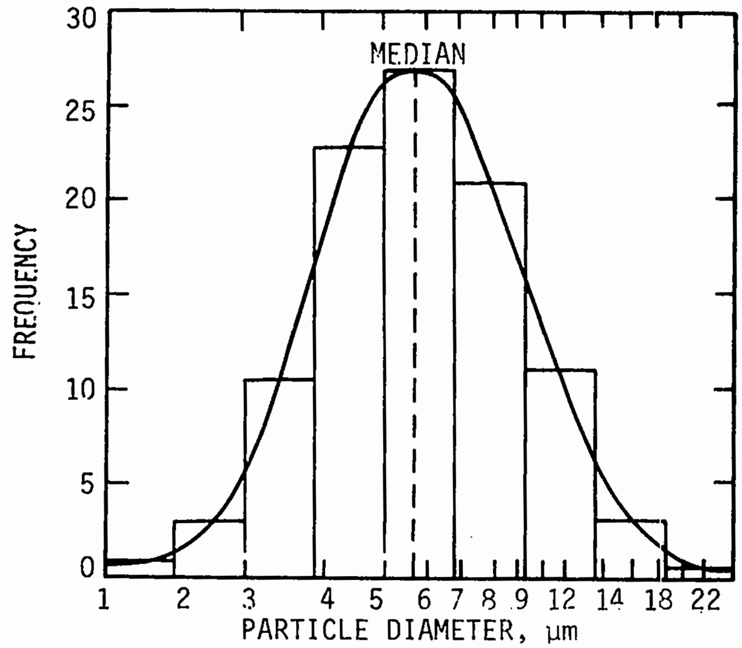


Figure 4.1-2. Histogram of a lognormal size distribution. (Reprinted by permission from Silverman, L., Billings, C. L. and First, M. W. Particle Size Analysis in Industrial Hygiene. Academic Press, 1971, p. 236.)

Both the geometric mean and the standard deviation can be determined easily by plotting the distribution data as a log-probability plot as shown in Figure 4.1-3. The geometric mean is the diameter equivalent to the 50 percent probability, and the standard deviation is the slope of the line. The latter can be determined simply by dividing the geometric mean by the particle size at the 15.78 percent probability (size d_1 in Figure 4.1-3) or by dividing the particle size at the 84.13 percent probability (size d_2 in Figure 4.1-3) by the geometric mean size.

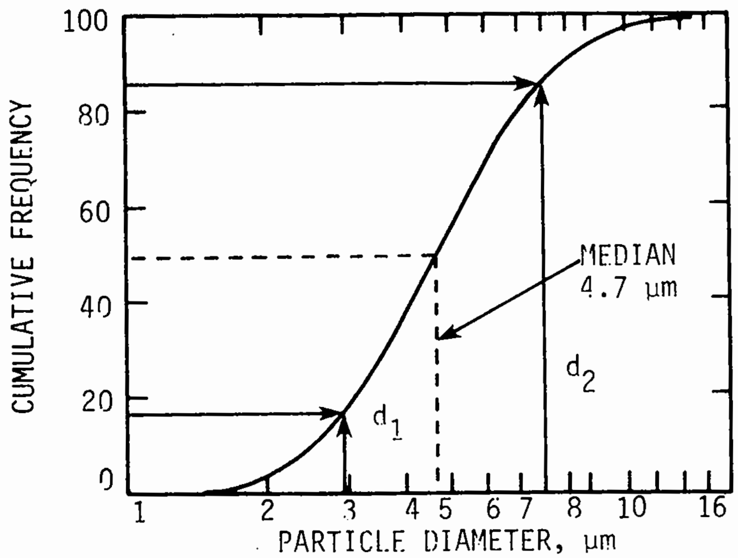


Figure 4.1-3. Cumulative lognormal size distribution. (Reprinted by permission from Silverman, L., Billings, C. E., and First, M. W. Particle Size Analysis in Industrial Hygiene. Academic Press, 1971, p. 239.)

Aerosol distributions may exhibit more than one peak. The hypothetical distribution shown in Figure 4.1-4 is called bimodal. This type of aerosol distribution is more difficult to characterize. In some cases, it may be possible to handle the distribution as two separate lognormal distribution aerosols. More detailed discussions of aerosol distributions are presented in references 4, 11, and 12.

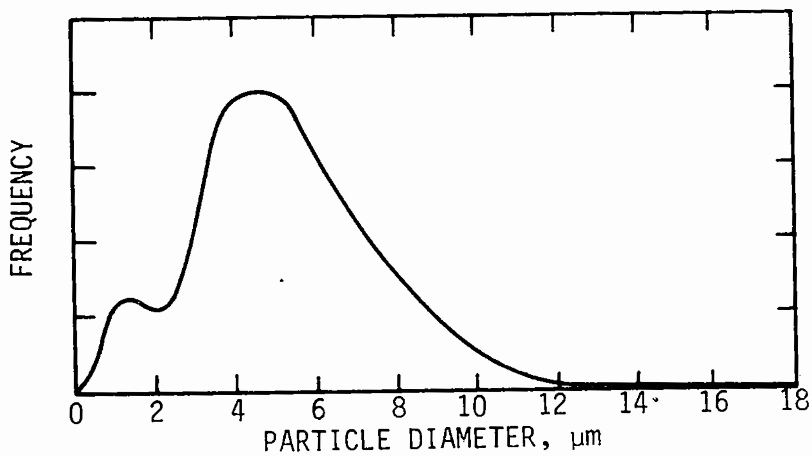


Figure 4.1-4. Bi-modal aerosol distribution.

4.1.1.2 Aerodynamic Properties. Each type of particulate control device uses one or more particle collection mechanisms. Those are the fundamental physical tools available to an equipment designer.

Impaction. Inertial impaction is the mechanism most frequently used to remove particulate matter. Particles have a much greater mass, and therefore much greater inertia when in motion, than the surrounding gas. Heavy particles resist changes of gas flow and cross gas streamlines because of their inertia. As a gas stream approaches an obstacle, the gas molecules pass on either side of it, leaving the particle propelled toward the obstacle by its inertia. If the particles are too small they flow with the gas molecules and pass around the obstacle. Figure 4.1-5 illustrates these phenomena relative to different sized particles. Low-energy impaction conditions separate particles with aerodynamic diameters above 50 μmA. High-energy impaction conditions effect separation of particles with aerodynamic diameters above a few tenths of a micrometer. Particles with aerodynamic diameters below a few tenths of a micrometer can not be separated by inertial impaction under normal conditions.

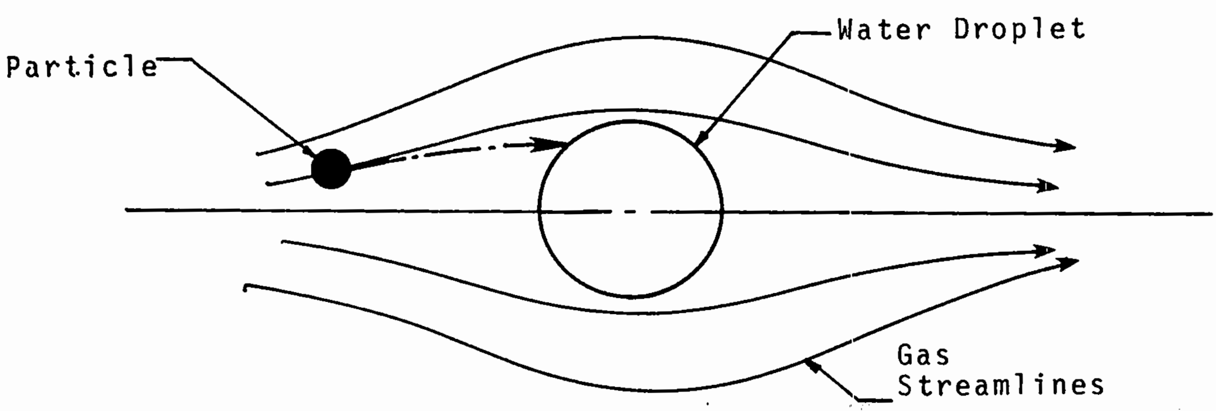


Figure 4.1-5. Impaction of particles on a target in a moving gas stream.

Efficiency of impaction collectors is related to an impaction parameter: a ratio of drag to viscous forces. The Stokes number, K_I, is commonly used to relate impaction efficiency.

$$K_I = \frac{Cd_p^2 \rho_p v}{18 \mu D_c} \qquad \text{(Eq. 4.1-2)}$$

where

K_I = Stokes number.
C = Cunningham slip factor, dimensionless.
d_p = particle diameter, µmA.
ρ_p = particle density, g/cm³.
v = particle velocity, cm/s.
D_c = diameter of collector, cm.
μ = gas viscosity, kg/m - s.

The impaction mechanisms become progressively more effective as the impaction parameter increases. The strong particle size dependence of inertial impaction is indicated by the fact that impaction is proportional to the square of the particle size.

Particle separation from a gas stream can also occur by a mechanism known as interception. The particle is intercepted by an obstacle if the particle radius is as large as or larger than the streamline displacement. Interception results in an increase over the amount of particle collection that is predicted by impaction alone. Interception is similar to, and can be considered a form of impaction. As illustrated in Figure 4.1-6, interception occurs when particle size and gas streamline displacement values are comparable. Particles in the size range above a few micrometers are susceptible to interception.

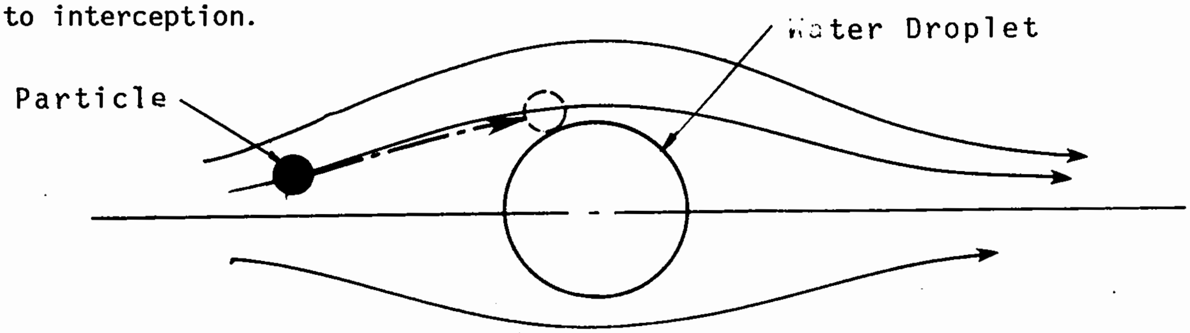


Figure 4.1-6. Interception of a particle on a target in a moving gas stream.

Diffusion. Particles in the same size range as molecules (10^{-3} μm) and up to a few tenths of a micrometer experience random movement due to collisions with gas molecules. The diffusion rate of a particle (D_p) can be determined by the Stokes-Einstein equation:

$$D_p = \frac{CKT}{3\pi\mu d_p} \qquad \text{(Eq. 4.1-3)}$$

where

D_p = diffusivity of particle, cm^2/s.
K = Boltzman constant, ($g - cm^2/s^2 - {}^\circ K$).
T = absolute temperature, K.

The effectiveness of this particle collection mechanism is proportional to the particle diffusivity which is inversely proportional to the particle size, as indicated above. Thus high diffusion rates occur for very small particles (0.001 to 0.1 μm), but diffusion is negligible for large particles. Particle diffusion is illustrated in Figure 4.1-7.

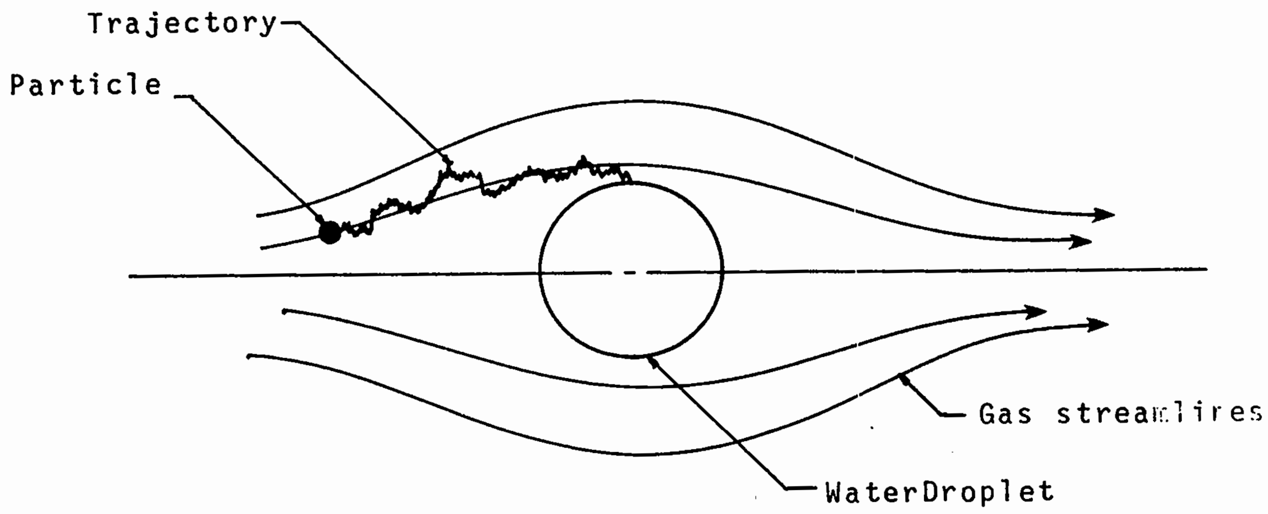


Figure 4.1-7. Diffusion of a particle to a target in a moving gas stream.

Settling. Movements of particles in the atmosphere are influenced by two main forces: gravity and drag. When particles are settling, gravitational force is pulling downward and drag is pushing upward. After sufficient time, the forces become equilibrated, and the particles reach their terminal settling velocity. To determine the settling velocity (V_t) for ideal situations, the Stokes terminal velocity equation can be used:

$$V_t = \frac{d_p^2 \ (\rho_p - \rho_g)g}{18 \ \mu} \qquad \text{(Eq. 4.1-4)}$$

As with inertial impaction, the effectiveness of settling is proportional to the square of the particle diameter. This mechanism becomes important in air pollution control systems only when the particle size is above 5 µmA and when the gas flow conditions are not highly turbulent.

Electrostatic Attraction. Particles are charged with unipolar ions, and are subjected to a strong electrical field. Movement of particles to a collection surface is primarily dependent on the balance between the electrostatic force and the aerodynamic resistance. Random diffusion charging contributes to the initial charging of the particles. Effectiveness of electrostatic attraction is basically related to the square of the particle aerodynamic diameter because larger particles can sustain a greater number of charges.

4.1.1.3 Physical Phenomena. Condensation and agglomeration can alter a particle size distribution and thereby have a significant impact on the aerodynamic behavior of the particles. Light scattering is important because opacity of the stack effluent is sometimes used to evaluate the effectiveness of the particulate control systems.

Condensation. Condensation of water vapor on suspended particles occurs whenever a degree of supersaturation is available around the particles. In industrial gas cleaning, three methods are available to effect particle growth by condensation: (1) mixing produces supersaturation by combining two saturated gas streams of different temperatures; (2) steam injection introduces steam into the gas stream, and (3) an adiabatic expansion method, which is available in venturi scrubbers.[13] A psychrometric chart indicates the appropriate temperature levels and amounts of water vapor available for use in particle growth by condensation.

The main benefit from condensation of water vapor on particles is the increase in their mass and size, which makes them easier to collect in inertial removal systems. Collection can be further enhanced by taking advantage of forces acting on the particles induced by a temperature gradient (thermophoresis) and vapor condensation (Stefan flow).[14] Superimposition of these effects can improve collection.

4.1.1.4 Agglomeration. When particles collide with each other during diffusion or turbulent motion they may adhere to each other and become combined or agglomerated particles. The rate of agglomeration depends mainly on particle concentration and is virtually independent of particle size, as shown by the following differential equation:

$$-\frac{dN}{dt} = kN^2 \qquad \text{(Eq. 4.1-5)}$$

where

k = rate constant.

N = number of particles per unit volume at time t.

Integration of Equation 4.1-5 from time zero to time t for an initial particle concentration (N_o) is:

$$\frac{1}{N} - \frac{1}{N_o} = kt \qquad \text{(Eq. 4.1-6)}$$

Agglomeration rate constant values (k) can be estimated for homogeneous and heterogeneous systems by the following:

$$\text{homogeneous system:} \quad k = \frac{4KTC}{3\,\mu} \qquad \text{(Eq. 4.1-7)}$$

$$\text{heterogeneous system:} \quad k = \frac{2KTC}{\mu} \qquad \text{(Eq. 4.1-8)}$$

for reference purposes, the homogeneous rate constant for air at 20°C is 3 x 10^{-10} cm^3/s. Values for agglomeration rate constants are also influenced by pressure and turbulence conditions. Increased pressure and greater turbulence separately enhance the probability of particle collision, and thus increase the agglomeration rates.[7]

4.1.1.5 Light Scattering. When white light strikes a suspended particle, a certain amount of light (depending on particle size, shape, composition, and surface configuration) is scattered irregularly in all directions. Particles scatter light in a degree proportional to their sizes. Supermicrometer particles scatter light proportional to diameters to the sixth power.[8]

4.1.2 Selection and Application of Particulate Control Devices

Each application of a particulate control system is unique to a degree. No general selection method can guarantee an environmentally and economically acceptable installation. Instead, it is necessary to carefully match process effluent characteristics with regulatory requirements of control device performance capabilities and control system costs. This section introduces some of the general issues involved in the selection and application of particulate control systems. More detailed information is presented in Sections 4.2 through 4.6.

4.1.2.1 Performance Capabilities. Most particulate control devices operate as combinations of the particle collection mechanisms discussed in Section 4.1.1. One or more mechanisms may be operative in any given device; the limitations of such mechanisms become the performance limits of the device. Table 4.1-1 presents the mechanisms normally active in the major types of particulate control devices. The effectiveness of the mechanisms depends on the design of the unit (e.g., gas velocity, device geometry, liquid utilization rate). Performance is typically characterized in terms of collection efficiency:

$$\text{Efficiency} = \frac{\text{inlet mass loading} - \text{outlet mass loading}}{\text{inlet mass loading}} \times 100 \qquad \text{(Eq. 4.1-9)}$$

The penetration fraction (P_t), defined in Equation 4.1-10, is a somewhat simpler measure of control device performance; and it is related to collection efficiency as indicated in Equation 4.1-10.

$$\text{Penetration} = \frac{\text{outlet mass loading}}{\text{inlet mass loading}} = 1\text{-efficiency}/100 \qquad \text{(Eq. 4.1-10)}$$

The penetration term is easier to use when evaluating high efficiency control devices and series of particulate control devices, and when using the computerized models developed for certain types of collectors. Due to the size dependence of the particle collection mechanisms the collection efficiency (or penetration) is a size-specific value. A set of values for various particle sizes is a penetration curve.

4.1.3 Control System Design

Proper selection of particulate control systems requires simultaneous consideration of regulatory requirements, performance limits, effluent

TABLE 4.1-1. PARTICLE CAPTURE MECHANISMS NORMALLY ACTIVE IN CONVENTIONAL PARTICULATE CONTROL DEVICES

Control device	Principal particle capture mechanism	Particle size dependence[a]
Settling chamber	gravity settling	d_p^2
Momentum separator	gravity settling	d_p^2
	inertial separation	d_p^2
Large-diameter single cyclone	inertial separation	d_p^2
Small-diameter multiple cyclones	inertial separation	d_p^2
Fabric filters	impaction on dry surfaces	d_p^2
	interception	d_p
	diffusion to dry surfaces	$1/d_p$
Electrostatic precipitator	electrostatic attraction	d_p^2 and $1/d_p$
	gravity settling	d_p^2
Wet scrubber	impaction on surfaces	d_p^2
	impaction on liquid droplets	d_p^2
	diffusion to wetted surfaces	$1/d_p$
	diffusion to liquid droplets	$1/d_p$
Incinerator	particle oxidation	$1/d_p$

[a]Based on particle capture mechanism.

characteristics, and cost. The control device must have the capability to maintain continuous compliance regardless of short-term fluctuations in the effluent composition, flow rate, and particle size distribution.

Control Device Sizing. Most particulate control devices (for example, baghouses and electrostatic precipitators can suffer performance degradation at high effluent gas stream velocities. A fundamental design problem is the sizing of the control device to balance the need for a large unit (low gas velocity) with the capital cost. The consequences of undersizing (high gas velocities) can be frequent noncompliance periods. The sizing of a control device should also accommodate anticipated operational changes; for example increases in process throughput and/or effluent gas temperature can lead to inadequate efficiency. A related problem is failure to properly size the support systems, such as solids removal equipment, by inadequately assessing the effluent conditions such as particulate mass loadings or bulk density.

Instrumentation. Control devices installed without proper instrumentation may be prone to frequent malfunctions and excessive emission periods. Examples are a fabric filter on a high-temperature source without temperature monitors and a wet scrubber on a combustion source without pH monitors. Proper instrumentation is necessary to provide an early warning of impending problems and to assist in diagnosis of underlying factors.

Accessibility. No particulate control system is completely maintenance-free. Control devices are normally subjected to multiple physical insults including abrasion, corrosion, mechanical shocks, moisture, high temperature, and high voltage. The designer and purchaser must decide what additional capital cost is justifiable to minimize future maintenance cost.

Power Input - The collection efficiency of a particulate control system is generally associated with power input. As power input increases the particulate emissions usually decrease. What emission level is affordable and justifiable, given the energy demand? This question is complicated by uncertainty over actual effluent gas stream characteristics (e.g., particle size distribution) and the lack of site specific empirical models relating power input to collection efficiency.

Corrosion - Catastrophic failure due to corrosion can result from inaccurate assessment of gas stream conditions during steady-state or start-up conditions. A contributing factor can be failure to consider the variability of effluent vapor concentrations caused by variability of process operations. To the degree economically feasible, particulate control equipment should be designed and fabricated to withstand worst-case conditions.

Abrasion - Large particles suspended in a fast moving gas stream are abrasive. Fabric filters are particularly vulnerable to abrasion near the gas inlets. Precleaners can be installed, but usually increase both capital cost and energy demand (increased fan energy).

Moisture and Freezing - Moisture and freezing can adversely affect wet scrubbers and any control device using compressed air (pulse-jet fabric filters and electrostatic precipitators with compressed air rappers). The solution to moisture problems in dry collectors are the inclusion of dryers on air compressors and drains on air reserve tanks. Wet scrubber lines should have drainage capability, particularly when operation is noncontinuous.

Ventilation Systems - The two basic parts of a ventilation system are the hood or air intake for initial capture of the particulate matter and the ductwork for transport of the particulate-laden gas stream to the control device. Inadequate design of a ventilation system can compromise overall performance.

The hood must be sized and oriented to capture the maximum quantity of particles without requiring excessive gas volumes (a trade-off between performance and energy consumption). It makes little sense to install a high-efficiency control device if a major portion of the particles are not captured initially. The hood should be as close as possible to the point of generation without interfering with equipment movement; it should be oriented to minimize cross-drafts and to take advantage of thermal drafts.

The ductwork leading from the hood (or pickup point) to the control device must be sized to provide the needed transport velocity--generally between 15 and 25 m/s, depending on particle size distribution.[15] Layout of ductwork should minimize energy losses indicated by static pressure drops, and should minimize air inleakage. If the source is hot, insulation may minimize temperature drops.

Solids Removal Equipment - The basic functions of the solids removal equipment are to remove collected particulate from the device as rapidly as it is collected and to deliver the material to an environmentally acceptable disposal area. Solids removal is one of the most frequent problem areas affecting particulate control equipment.

Most particulate systems operated at elevated temperature must use hopper heaters, insulation, or weather enclosures, or combinations of these to keep the collected particulate hot to maintain free flow. Hopper temperature control can also reduce corrosion resulting from condensation.

Delivery of the solids to a disposal site or to a temporary storage site must be done without resuspension of the material. As with inadequate hood capture, a seemingly small degree of resuspension can compromise any gains achieved by a high-efficiency collector. This often happens when solids are discharged with a significant free fall (directly below a discharge valve or between two conveyors) or when a temporary storage pile is unprotected from winds.

Fans - Movement of particulate-laden gas stream from the process, through the control device, and out the stack is controlled by the fan. Fan selection is critical to proper operation of the overall system. Although the forward curved design has high efficiency, it is vulnerable to particulate buildup on the blades so it is very rarely used in particulate control systems. The backward-curved design also has relatively high energy efficiency, and it is also susceptible to particulate buildup. This type of fan is normally used only on the "clean side" of the particulate control device to provide induced draft. The most rugged type is the radial blade design fan which can withstand high dust loadings without excessive vibration and therefore, can be used on either the clean or the dirty side.

There can be fan problems with fans initially selected properly. They must provide adequate gas flow and static pressure despite nonideal ventilation system design or fan inlet configuration. Air inleakage can lead to lower-than-expected gas stream temperatures and hence to higher horsepower.

In summary, the design of a control device involves the balancing of numerous factors. The design decisions must be made specifically for the source. The ultimate success of the control system depends at least partially on a realistic evaluation of the characteristics of the effluent gas stream and the entrained particulate matter distribution.

4.1.3.1 System Operation and Maintenance. Continuous compliance with air pollution control regulations depends largely on proper operation and maintenance such as preventive maintenance programs, recordkeeping procedures, and operator training programs. An important aspect of training is full awareness of potential safety problems.

Prevention Maintenance - An integral part of a preventive maintenance program is routine inspection of equipment. Depending on the potential for malfunctions and the consequences of excess emissions (toxicity, quantity), inspection could be done daily, weekly, or monthly. For most equipment, the internal and external conditions of the equipment must be noted during inspection.

An adequate spare parts inventory should be maintained to prevent excessive downtime or excessive emissions while operating under nonoptimal conditions. Determination of what is necessary depends partially on the local availability of supplies and on the costs of parts relative to the cost of equipment nonavailability.

Recordkeeping - The logical first step in recordkeeping is to make sure that instruments are properly located and are functioning normally. Most instruments, even supposedly simple devices, require calibration. There is little sense in faithfully keeping records that are incorrect or misleading.

Only the data that must be evaluated to determine developing problems or nonoptimal conditions need to be recorded. If large quantities of unnecessary data are logged, the meaningful data may be lost.

In addition to the normal operating records, diagnostic records should be recorded during forced outages or routine maintenance periods to indicate the type and location of component failures (e.g., bag failure location, discharge wire breakage type and location). Such diagnostic records can be as simple as copies of repair work orders with comments by maintenance personnel.

Training - Particulate control systems are complex and expensive. Operator training is helpful to ensure proper and safe operation. Training should emphasize procedures for startup and shutdown to minimize damage to the unit. Early signs of developing problems should be stressed.

The importance of safety training for operating and maintenance personnel cannot be overemphasized. A particulate control system may represent a combination of a very large number of potential hazards, including oxygen deficiencies, toxic gases, high temperatures, high voltages, hot dust (hoppers), high noise levels, and moving machinery. As a minimum, training should address confined space entry procedures, selection and use of protective equipment, and safe work practices.

REFERENCES

1. U.S. Department of Health, Education, and Welfare. National Air Pollution Control Administration. Control Techniques for Particulate Air Pollutants. AP-51, January 1963.

2. Fuchs, N. A. Mechanics of Aerosols. Pergamon Press, London, 1964.

3. Davies, C. N. Air Filtration. Academic Press, Inc., New York, 1973.

4. Silverman, L., C. E. Billings, and M. W. First. Particle Size Analysis in Industrial Hygiene. Academic Press, Inc., New York, 1971.

5. Green, H. L., and W. R. Lane. Particulate Clouds, Dusts, Smokes, and Mists (2d ed.). Van Nostrand, Princeton, New Jersey, 1964.

6. Davies, C. N. Aerosol Science. Academic Press, Inc., 1964.

7. Hesketh, H. E. Understanding and Controlling Air Pollution. Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, 1974.

8. Hesketh, H. E. Fine Particles in Gaseous Media. Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, 1977.

9. Drinker, P., and T. Hatch. Industrial Dusts (2d ed.). McGraw-Hill, New York, 1959.

10. Hidy, G. M., and J. R. Brock. The Dynamics of Aerocolloidal Systems, Vol. 1. Pergamon Press, London, 1970.

11. Yeshida, T., et al. Particle Growth by Condensation and Coagulation--Basic Research of its Application to Dust Collection. In: Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. I. EPA-600/7-77-004d, February 1979.

12. Calvert, S., J. Goldshmid, D. Leith, and N. Jhaveri. Feasibility of Flux Force/Condensation Scrubbing for Fine Particle Collection. EPA-650/2-73-036, October 1973.

4.2 MECHANICAL COLLECTORS

Mechanical collectors comprise a broad class of particulate control devices that utilize the gravity settling, inertial, and dry impaction mechanisms. Because their performance capability is limited to relatively large particles and regulatory requirements have become more stringent, use of mechanical collectors has gradually declined and they are now used primarily as precleaners. Mechanical collectors are reasonably tolerant of high dust loadings, are not susceptible to frequent malfunction if properly designed and operated, and are adequate control devices for some applications.

There is great diversity in the design and operating principles of the various types of mechanical collectors. Most penetration performance data for mechanical collectors were obtained from 1940 through 1970. Since 1970 attention has shifted to more sophisticated particulate control devices. Consequently, only limited field data are available.

4.2.1 Types of Mechanical Collectors

The major classes of commercially available mechanical collectors are listed in Table 4.2-1.

TABLE 4.2-1. MAJOR TYPES OF MECHANICAL COLLECTORS

Type	Particle capture mechanism
Settling chamber	gravity settling
Elutriator	gravity settling
Momentum separator	gravity settling, inertial collection
Mechanically aided collector	inertial collection
Inertial centrifugal collector	inertial collection

The general characteristics of these devices are described in the remainder of this subsection. Later subsections address operating principles, design, operation, and performance.

4.2.1.1 Settling Chambers. Large particulate is removed by gravitational settling in settling chambers to protect downstream equipment from abrasion and excessive mass loadings.[1]

The two basic types are the simple expansion chamber and the multiple-tray settling chamber (Figure 4.2-1). The latter is a set of horizontal collection plates that reduce the distance a particle must fall to reach the collecting surface.[1,2] Thus the multiple-tray unit can collect somewhat smaller particles, which settle more slowly.[2]

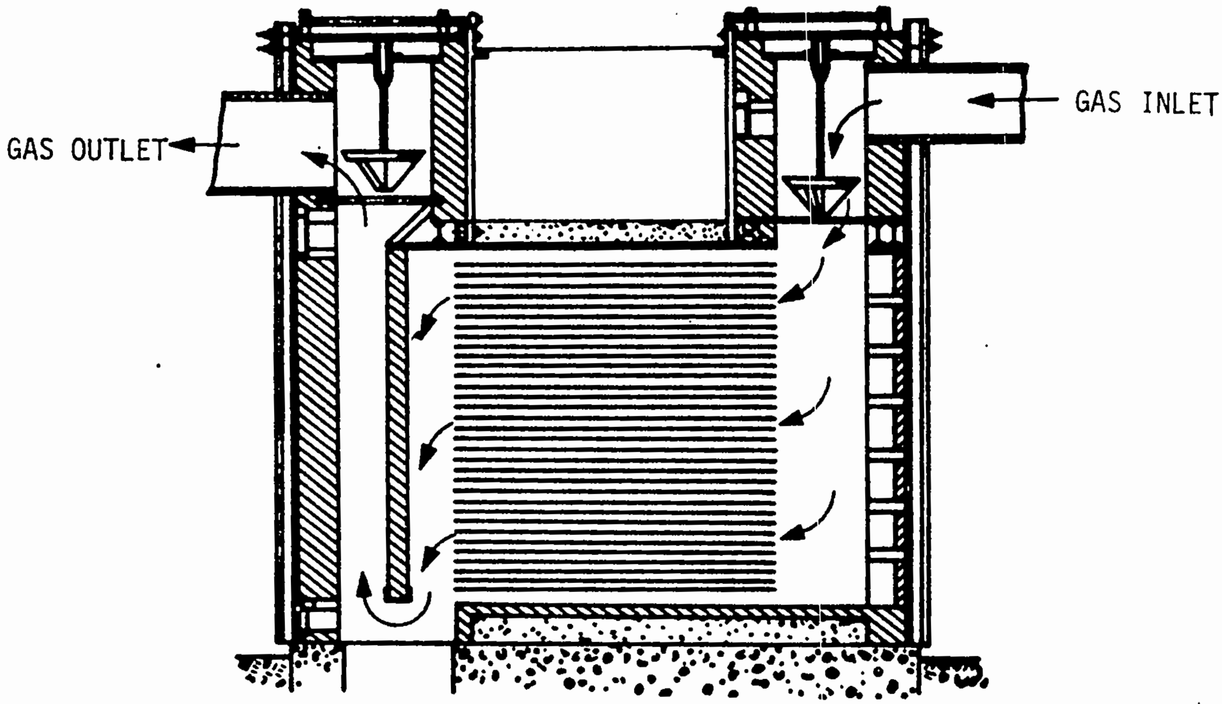


Figure 4.2-1. Howard multi-tray settling chamber.

Reprinted with permission of McGraw-Hill Book Company.
John H. Perry, Chemical Engineers Handbook, 3rd edition. 1950

The settling chambers should be designed for low velocities with a minimum of turbulence so that the settling of particles is not disturbed. Typical superficial velocities range from 0.3 to 3 m/s.[3,4] Gas stream distribution across the chamber inlet is important.

4.2.1.2 Elutriators. An elutriator consists of one or more vertical tubes or towers in series into which a dust-laden gas stream passes upward at a velocity defined by the gas flow rate and the tube cross-sectional area.

Large particles with terminal settling velocities greater than the upward gas velocity are separated and collected at the bottom of the chamber. Smaller particles with lower settling velocity are carried out of the collector. The particle size collected may be varied by changing the gas velocity.

When size classification is desired for disposal or reintroduction into a process, a series of collectors may be used with increasing cross-sectional area. Typical uses of elutriators are in secondary metal operations, food and agricultural processes, and petrochemical industries.

4.2.1.3 Momentum Separators. The momentum separator uses a combination of gravity and particle inertia (momentum) to settle particles onto surfaces. The particles are separated from the moving gas stream by providing a sharp change in direction of gas flow so that momentum carries the particles across the gas streamlines and into the hopper.

The simplest versions provide a 90- to 180-degree turn to separate large particles[5,6] (see Figure 4.2-2, a and b). Baffles can be added to increase the number of turns and thereby provide a modest increase in collection (see Figure 4.2-2c).

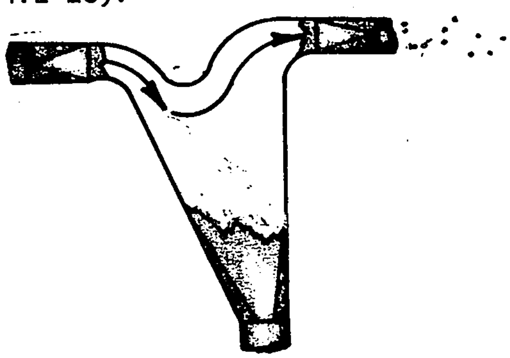


Figure 4.2-2. a. Simple momentum separator.

Reprinted from: Alden, J. L. Design of Industrial Exhaust Systems, 3rd Ed., The Industrial Press, New York, 1959.

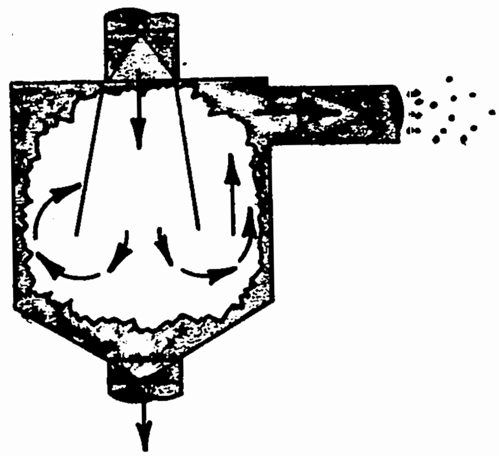


Figure 4.2-2. b. Simple momentum separator.

Reprinted from: R. F. Jennings, J. Iron Steel Inst. Vol. 164, page 305, 1950.

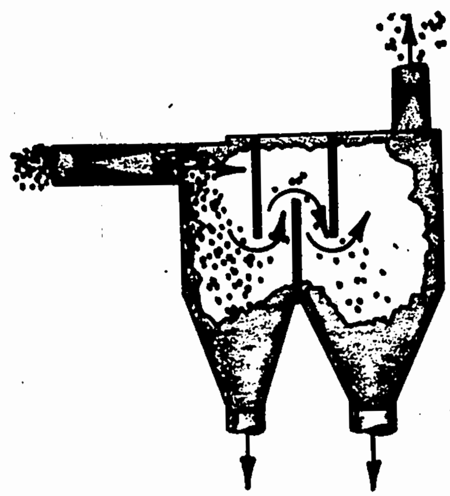


Figure 4.2-2. c. Baffle-type momentum separator.

Reprinted from: L. Theodore and D. W. Buonicore. Industrial Air Pollution Control Equipment for Particulates, CRC Press, Inc., page 66, 1976.

The louver collector, a type of momentum collector shown in Figure 4.2-3, consists of a series of flat plates (blades) set at an angle to the gas stream. A large portion of the gas stream is required to make a sharp turn to pass through the plates. The momentum of the particles in the air stream results in movement of the particles in a path parallel to the louver surface and across the gas stream. Separation of the particles from the gas stream leads to concentration of the larger particles in a small portion of the gas stream.[7,8] Penetration is a function of louver spacing and gas volume.

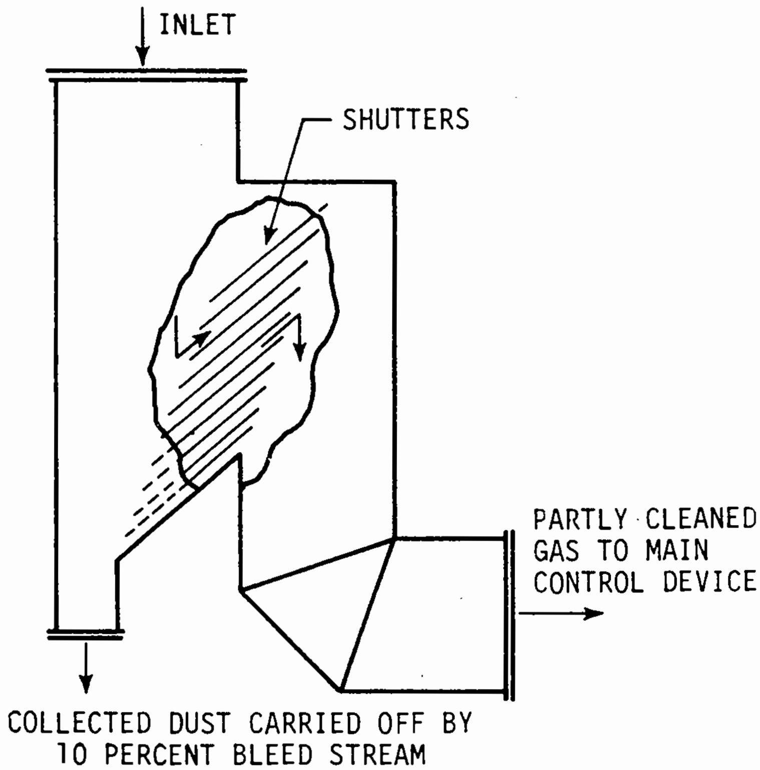


Figure 4.2-3. Louvered shutter type collector.

Reprinted from: Stairmand, C. J. Trans. Insti. Chem Engro - Vol. 29, page 356, 1951.

4.2.1.4 <u>Mechanically Aided Separators</u>. The separation mechanism of mechanically aided separators, like that of momentum collectors, is inertia. Mechanical acceleration of the effluent gas stream increases the effectiveness of the inertia separation so that these devices can collect smaller particles than the momentum devices. The improved performance, however, is gained at the expense of higher energy cost. Also, the devices are subject to abrasion by the action of large-diameter particles at medium to high velocities.

The most common of the mechanically aided collectors is a modified radial blade fan. The dust-laden air enters the collector perpendicular to the blade rotation, and by momentum the particles cross the air stream and concentrate at the side of the collector casing. The rapid acceleration of the gas stream imparted by the mechanical rotation of the blades maintains the concentrated particles in a narrow band which is then drawn off for particle separation in a more efficient collector.

Many collectors use this design principle, and many variations of this method are used to concentrate the particles into a smaller gas volume. In addition to modifications, scroll collectors and skimmers are also used.

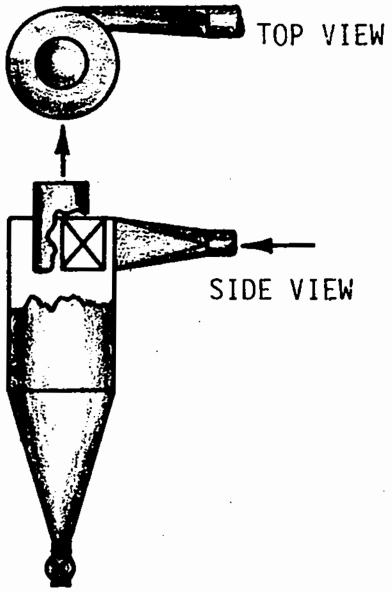
4.2.1.5 Cyclones. The cyclone collector is similar to the momentum collector in that inertia is used to separate the particles from a turning gas stream. In the cyclone the gas stream makes one or more circular turns, followed by a 180-degree turn to the outlet duct. Combined effects of a greater number of turns and higher gas velocity improve the particle collection capability above that of momentum collectors.

Cyclones can be classified into four basic categories according to the methods used to remove the collected dust and to introduce the gas stream into the unit.[9] Figure 4.2-4 illustrates the four types of cyclone collectors.

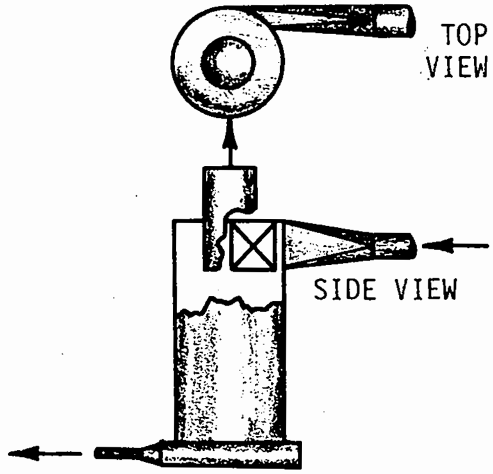
A vortex is created within the cylindical section of the cyclone by either injecting the gas stream tangentially or by passing the gas stream through a set of spin vanes. Because of inertia, the particles migrate across the vortex gas streamlines and concentrate near the cyclone walls. Near the bottom of the cyclone cylinder the gas stream makes a 180-degree turn, and the particles are discharged either downward or tangentially into hoppers below. The treated gas passes upward and out of the cyclone.

Simple cyclones. The simple cyclone consists of an inlet, cylindrical section, conical section, gas outlet tube, and dust outlet tube. A typical tangential-inlet, axial-outlet simple cyclone is shown in Figure 4.2-5.

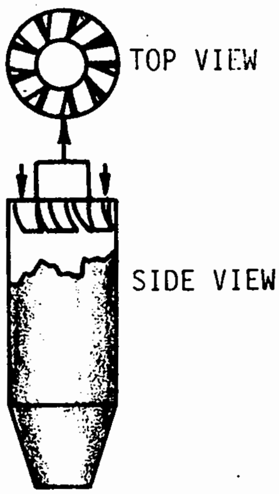
Particle separation is a function of the gas throughput and the cyclone cylindrical diameter. Particle inertia increases with increases in gas flow



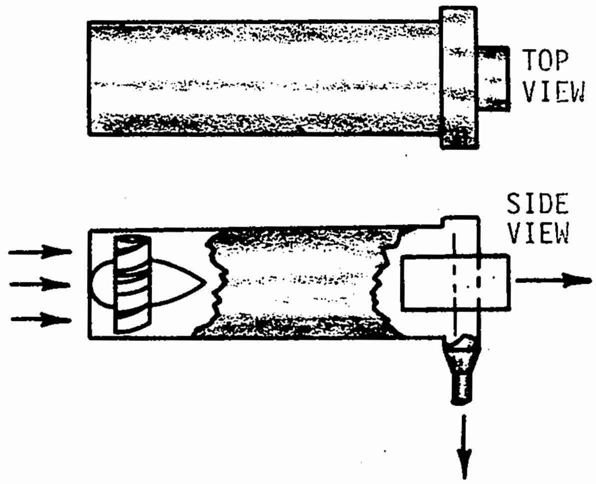
a. Tangential inlet, axial dust outlet



b. Tangential inlet, peripheral dust outlet



c. Axial inlet, axial dust outlet



d. Axial inlet, peripheral dust discharge

Figure 4.2-4. General types of cyclones.

Adapted from: Caplan, Air Pollution, A. Stern, Editor, Academic Press, 1968.

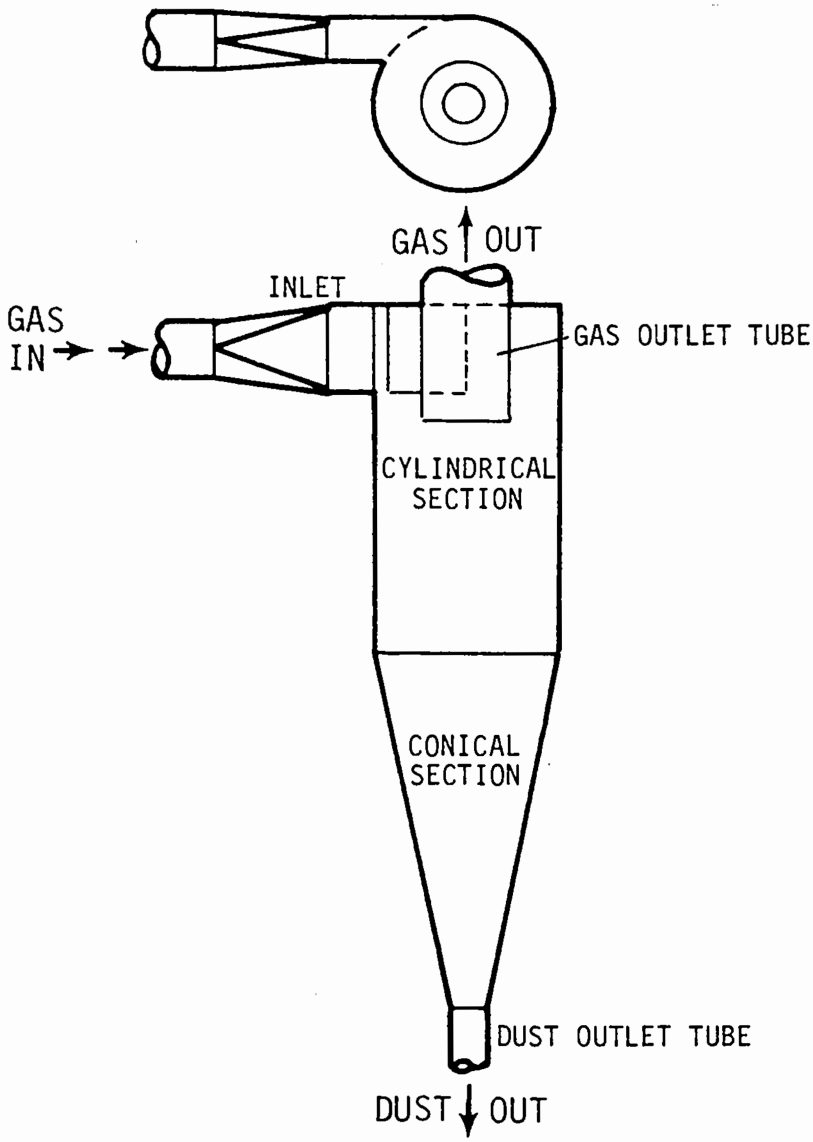


Figure 4.2-5. Typical simple cyclone.

rates and decreases in cylinder diameters, and collection efficiency increases accordingly. There is an upper limit, however, at which the increased turbulence caused by higher gas velocities can disrupt particle concentration.

Medium-efficiency single cyclones are usually less than 4 m in diameter and operate at static pressure drops of 0.50 to 1.50 kPa.[4] Overall collection efficiency is a function of the inlet particle size distribution.

Axial-inlet, axial-discharge cyclones. One common type of axial-inlet, axial-discharge cyclone is called the double-vortex cyclone. The collector consists of an air inlet at the bottom of a long cylinder with stationary turning vanes. The gas stream is placed in a vortex flow pattern upward through the cylinder. A secondary vortex is generated by either stationary vanes or injection nozzles outside of the inner vortex moving in a downward motion. The particles in the inner vortex move across the stream lines and into the downward-moving outer vortex. The concentrated particles are separated at the bottom of the unit as the outer vortex changes direction. The flow pattern is illustrated in Figure 4.2-6.

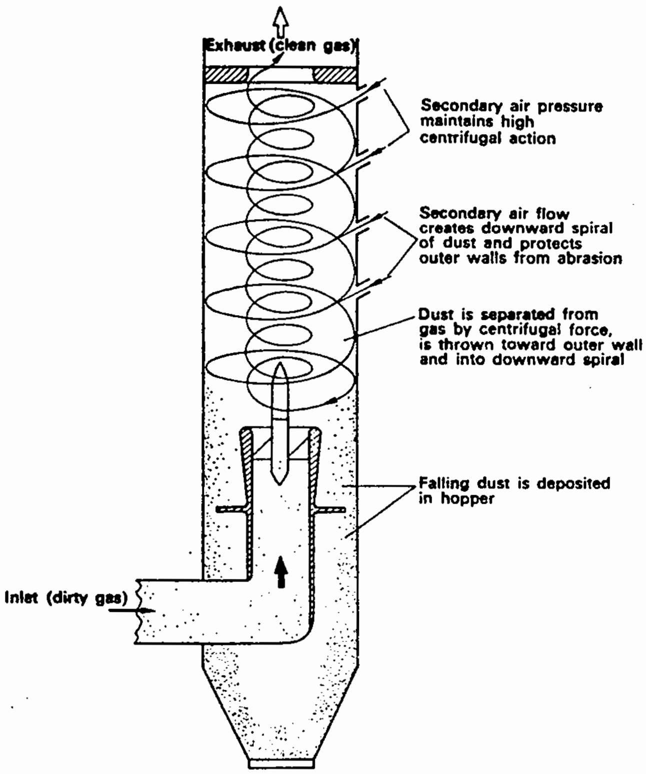


Figure 4.2-6. Flow pattern in a double-vortex cyclone.

Courtesy of Aerodyne Development Corporation.

The static pressure drop of the collector is between 3 to 6 kPa. Reported separation efficiencies are >99 percent for particles >6 µmA and >95 percent for particles >1 µmA.[10]

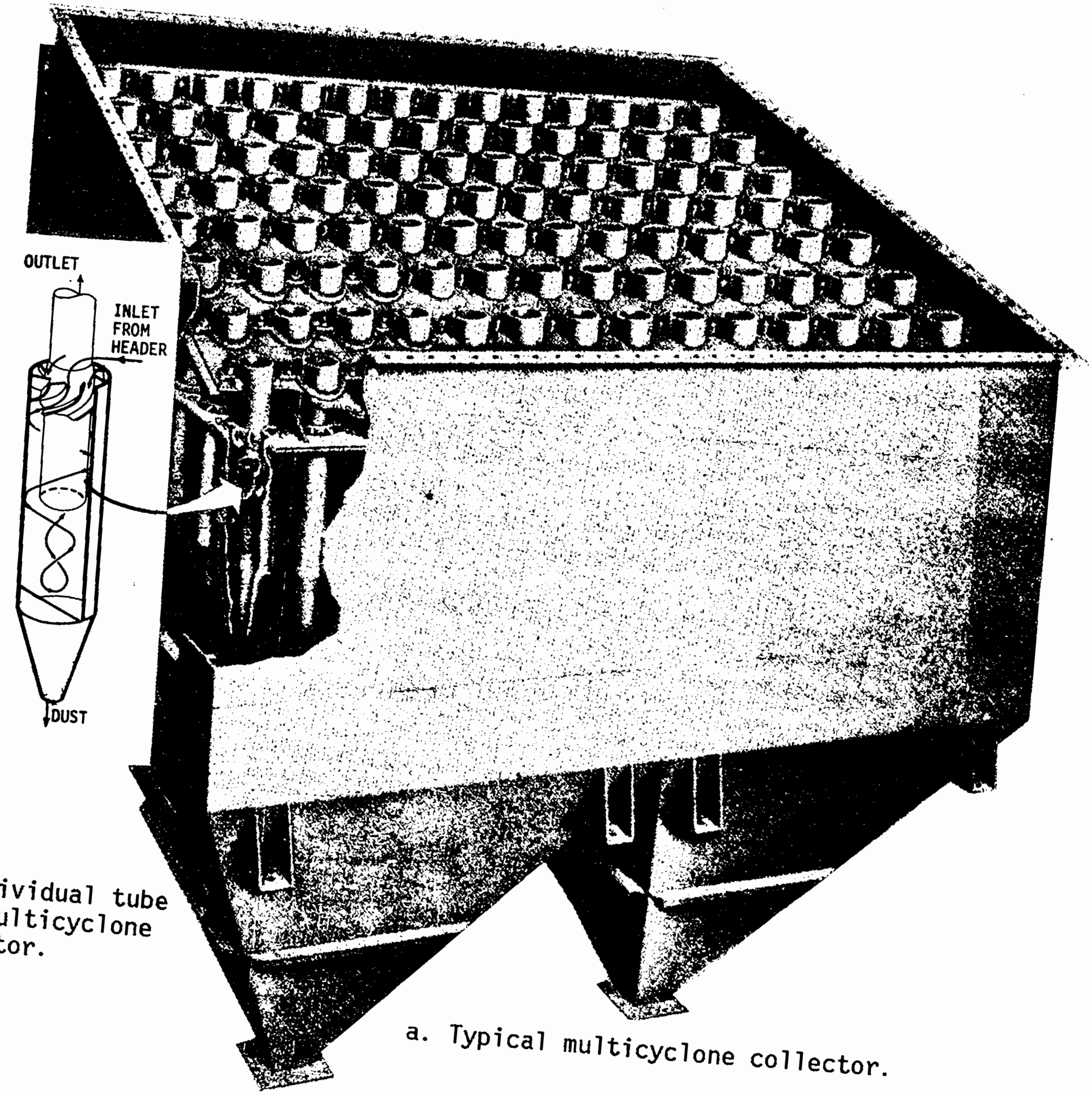
Multiple axial-inlet, axial-outlet cyclones. A multiple cyclone consists of numerous small-diameter cyclones operating in parallel. The high-efficiency advantage of small-diameter tubes is obtained without sacrificing the ability to treat large effluent volumes. A typical unit is shown in Figure 4.2-7a.

The individual cyclones, with diameters ranging from 15 to 60 cm, operate at pressure drops from 0.5 to 1.5 kPa. The inlet to the collection tubes is axial, and a common inlet and outlet manifold is used to direct the gas flow to a number of parallel tubes. A single tube from a typical multiple cyclone is illustrated in Figure 4.2-7b. The number of tubes per collector may range from 9 to 200 and is limited only by space available and by the ability to provide equal distribution of the gas stream to each tube. Properly designed units can be constructed and operated with a collection efficiency of 90 percent for particles in the 5 to 10 µmA range.[4]

Variation in performance is achieved by the use of several multicyclone banks in series or by the withdrawal of 10 to 20 percent of the gas.

Multiple axial-inlet, peripheral-discharge cyclones. The axial-inlet/peripheral-discharge cyclone is a variation of the multicyclone collector in that the gas is placed in a vortex motion by a fixed vane and the dust is concentrated at the collector tube wall by inertial force. The central core of the gas stream is relatively free of particles and is allowed to exit the collector tube axially. The outer portion of the gas stream (vortex) is withdrawn by an induced-draft fan for removal of the concentrated particles by a more efficient collector. The secondary collector system is operated at a lower static pressure than the main air flow to reduce reentrainment of the concentrated dust (Figure 4.2-8a).

A number of fixed impeller tubes are arranged in parallel and have a common inlet and outlet manifold. The secondary gas stream is passed through a settling chamber, then the concentrated particles are removed by a small high-efficiency cyclone. The secondary gas volume typically constitutes 10 to 20 percent of the primary gas stream. High collection efficiency may be achieved by using the collector tube banks in series and parallel arrangements to provide optimum flow volumes in each tube (Figure 4.2-8b).



b. Individual tube from multicyclone collector.

a. Typical multicyclone collector.

Figure 4.2-7. Multicyclone collector.

Figure a reprinted from: Joy Manufacturing Co. and Figure b reprinted from: Howden, James & Co. Ltd., 195 Scotland Street, Glasgow, C-5 efficiency may be achieved by using the collector tube banks in series and parallel arrangements to provide optimum flow volumes in each tube (Figure 4.2-8b).

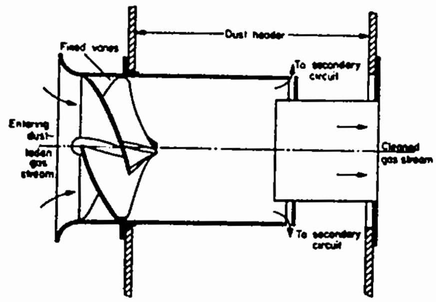


Figure 4.2-8a. Fixed-impeller straight-through cyclone.

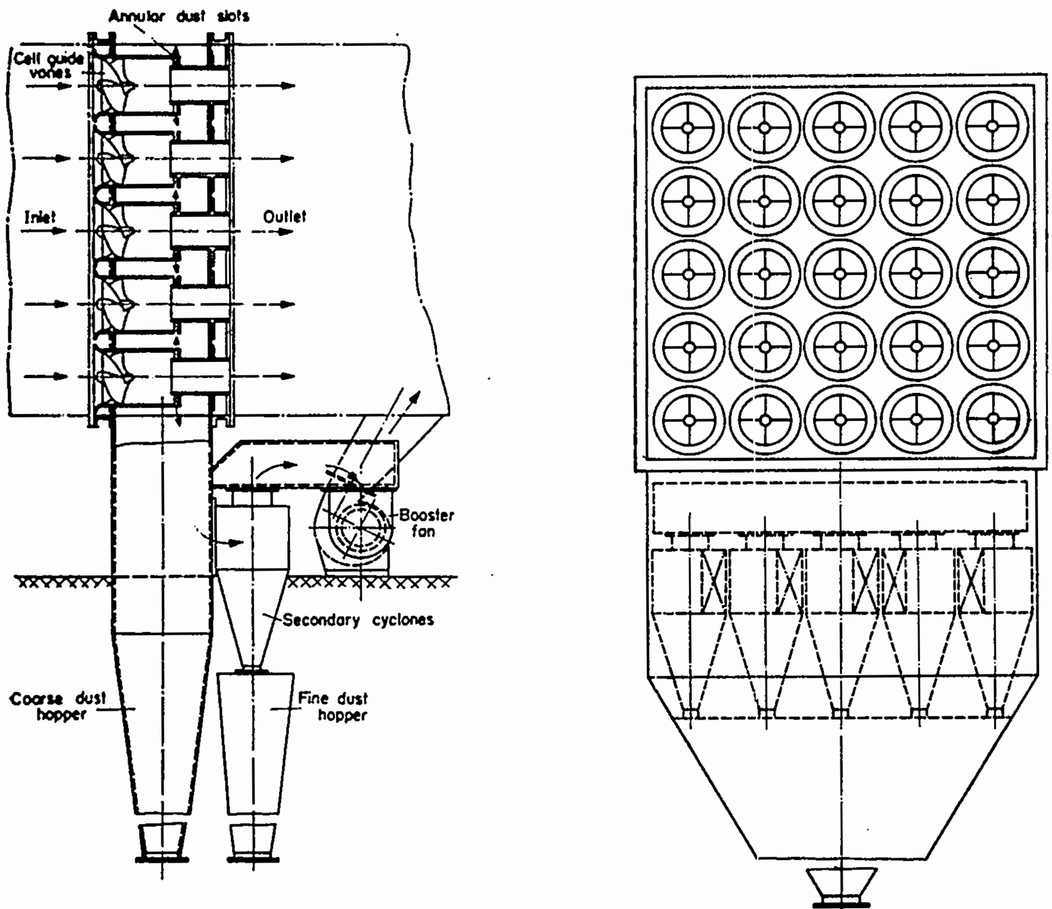


Figure 4.2-8b. Bank of fixed-impeller straight-through cyclones with secondary cyclone dust collector.

Reprinted with permission of Davidson and Co. Ltd., Belfast Publication, Ref. No. 387/61.

4.2.2 Operating Principles of Mechanical Collectors

Fundamental operating principles of the various mechanical collector designs are discussed in this subsection, with emphasis on theoretical aspects of penetration and pressure drop. Information concerning these specific collector types can be transferred with a reasonable degree of confidence to other mechanical collectors of similar geometric configuration with similar particle capture mechanisms.

4.2.2.1 Penetration.

Settling chambers. The following equations are a condensed summary of the approach presented by Theodore and Buonicore.[4] A similar approach is described in Crawford.[1] The performance limitations of settling chambers are examined by determining the fraction of particles of a given size that will be collected during the gas "treatment" time, t_R, defined in Equation 4.2-1.

$$t_R = \frac{BLH}{Q} \qquad \text{(Eq. 4.2-1)}$$

where t_R = residence time of gas stream in the settling chamber, s

B = chamber width, m

L = chamber length, m

H = chamber height, m

Q = gas flow rate, m^3/s

The vertical distance, h, through which a particle of specified aerodynamic diameter, d_i, will settle in this time period is simply t_R times the terminal settling velocity, V_T, of that particle.

$$h = V_t \times t_R \qquad \text{(Eq. 4.2-2)}$$

where V_t = terminal settling velocity of particle size i, m/s

The terminal settling velocity is calculated from Equation 4.2-3.

$$V_t = \frac{g \, \rho_p \, d_i^2}{18\mu} \qquad \text{(Eq. 4.2-3)}$$

where g = acceleration of gravity, 9.806 m/s^2

ρ_p = density of particle, kg/m^3

d_i = aerodynamic diameter of particle, μmA

μ = gas viscosity, kg/m-s

Equation 4.2-3 is reasonably accurate for particles with Reynold Numbers <1, which in this case is equivalent to aerodynamic particle diameters $\leq$80 μmA. Note that settling velocity is proportional to the aerodynamic particle diameter squared and inversely proportional to the gas viscosity.

The ratio of h/H represents the fraction of particles of a given size that will be collected.

$$h/H = \frac{V_t \times t_R}{(Q \times t_R)/BL} = \frac{V_t BL}{Q} \qquad \text{(Eq. 4.2-4)}$$

Penetration, P_i, is simply 1 minus the fractional efficiency.

$$P_i = 1 - h/H = 1 - \frac{V_t BL}{Q} \qquad \text{(Eq. 4.2-5)}$$

The total penetration is the sum of the penetrations for the various particle size increments. This simple approach is reasonably valid for particles in the diameter range of 1 to 80 μmA, which is the range normally of interest. To extend this type analysis to a wider particle size range, see Reference 4.

Equation 4.2-4 is based on the assumption of laminar flow throughout the chamber. Turbulent conditions will lead to higher penetration (lower efficiency) than predicted, especially for the smaller particle sizes.

As the gas velocity increases, the limiting velocity at which deposited particles may be reentrained into the gas stream may be exceeded. A theoretical equation for pickup velocity, V_p, is:

$$V_p = \left[\frac{4\ g d_i\ (\rho_i - \rho)}{3\rho}\right]^{0.5} \qquad \text{(Eq. 4.2-6)}$$

where V_p = pickup velocity, m/s
g = acceleration of gravity, m/s^2
d_i = particles diameter, i, m
ρ_ρ = particle density, kg/m^3
ρ = gas density, kg/m^3

Figure 4.2-9 shows a typical penetration curve for a settling chamber and Figure 4.2-10 shows a penetration curve based on dust measurements at a sinter plant.

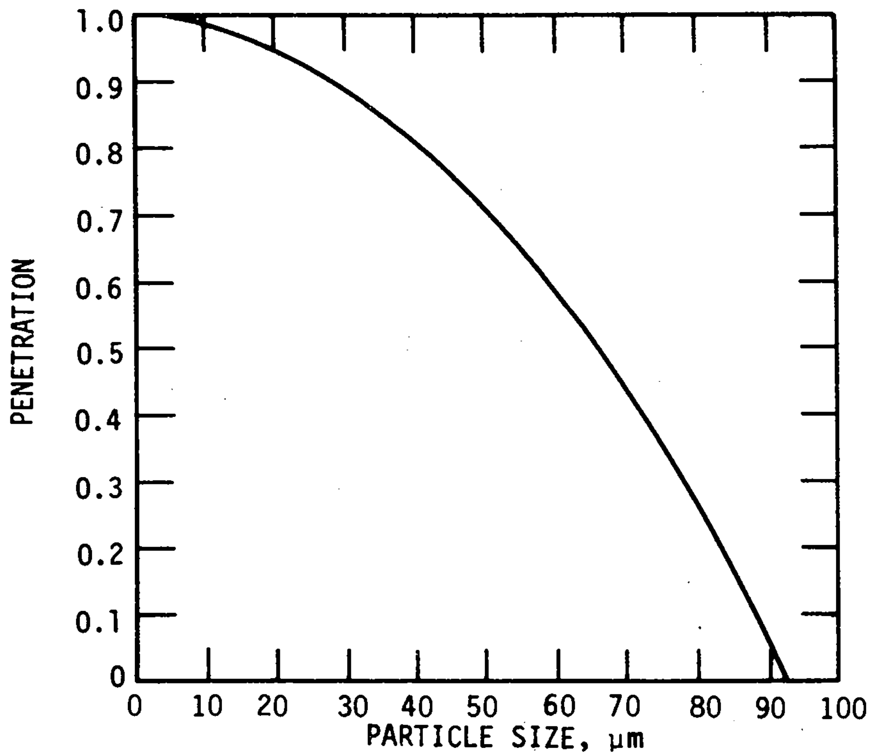


Figure 4.2-9. Typical size efficiency curve for settling chamber.

Adapted from data presented in Theodore and Buonicore, page 87.

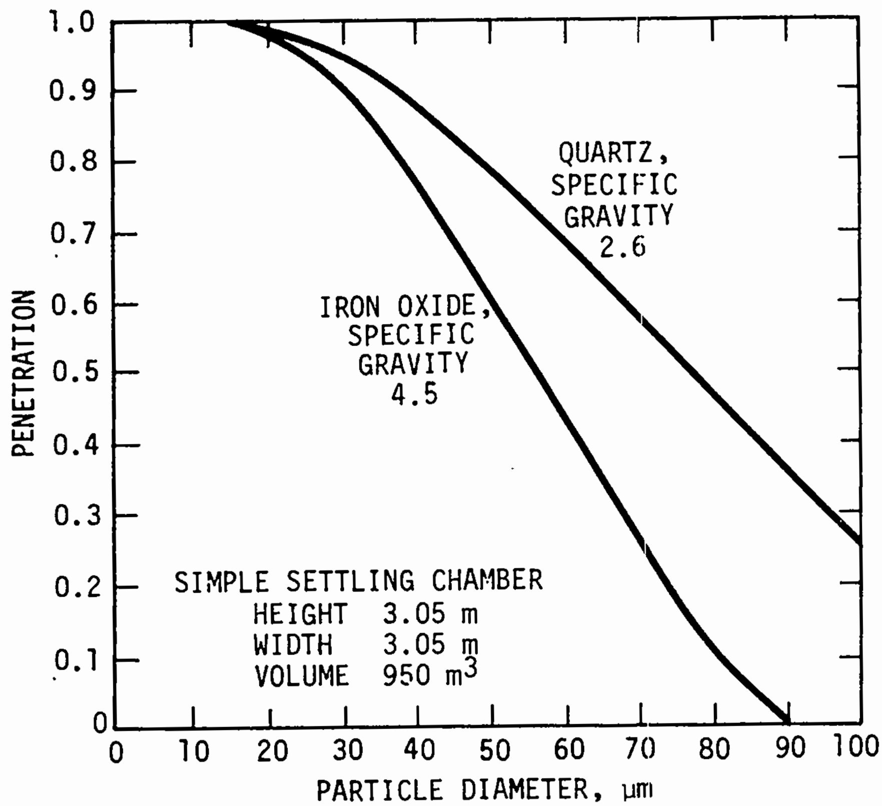


Figure 4.2-10. Penetration of dust through a settling chamber serving a sinter plant.

Adapted from data presented in Jennings, R. F., J. Iron Steel Inst. (London) Vol. 164, page 305, 1950.

Momentum separators. Particles are removed from a gas stream by use of the inertia of particles. A gas stream containing the particles is required to make a sharp change in direction.

The separation in most devices of this type is a combination of momentum mechanisms and particle settling mechanisms. The particles penetrate through the gas stream and are settled by gravity in hoppers. Collection may be by impingement on impaction surfaces or by use of secondary inertia separation to remove the concentrated particles (Figure 4.2-11).

A penetration curve, adapted from Reference 7, for a commercially available momentum separator is provided in Figure 4.2-12.

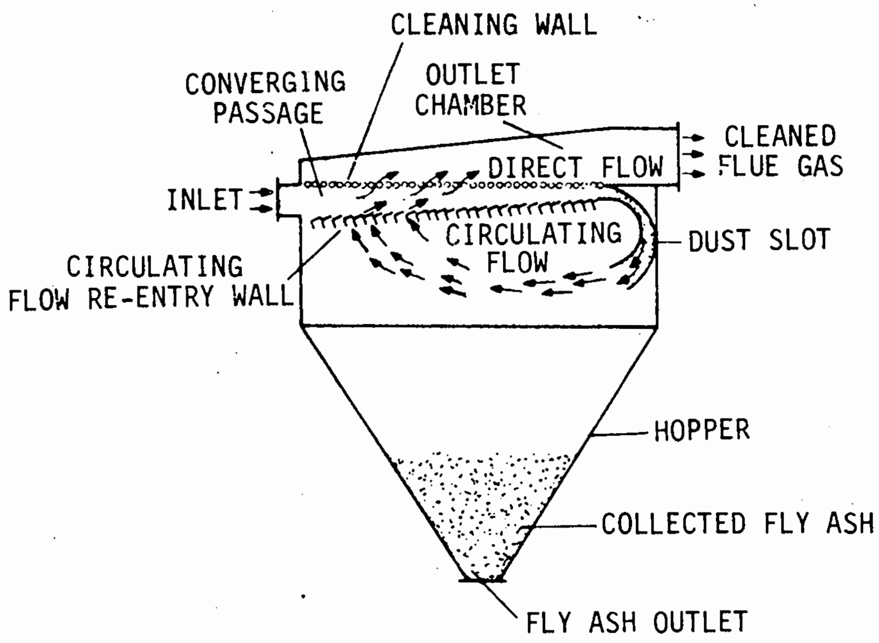


Figure 4.2-11. Momentum separator.

Reprinted from: Jackson, R., British Coal Utilization Research Association Bulletin, Vol. 24, p. 221, 1962.

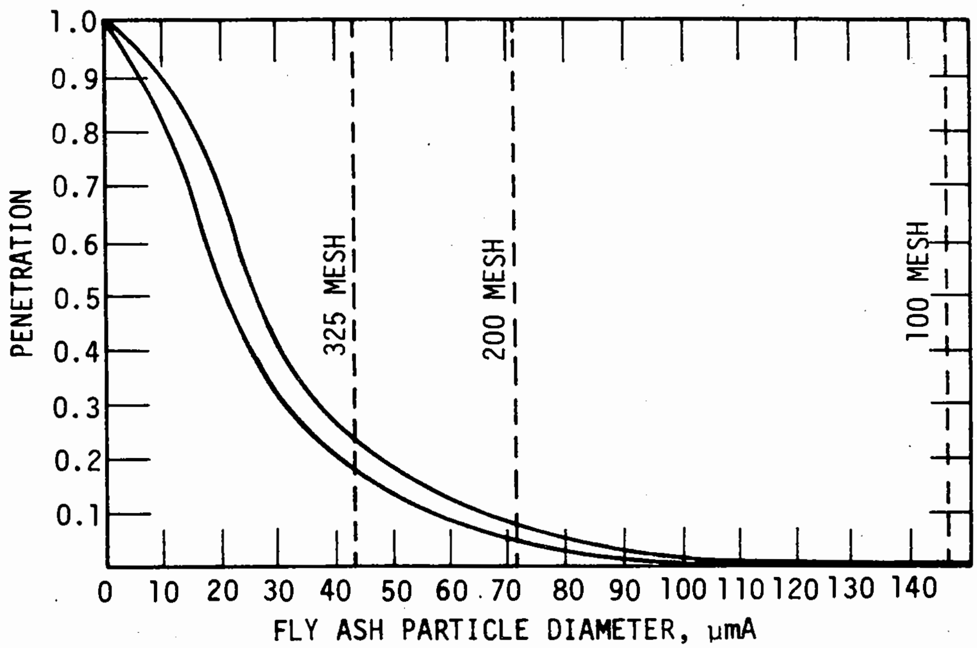
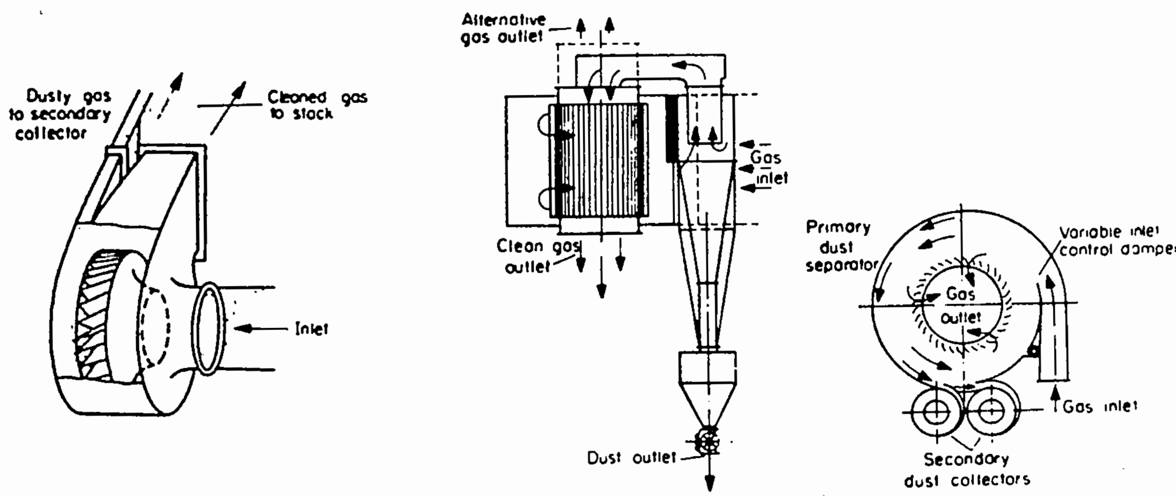


Figure 4.2-12. Penetration of fly ash through two momentum separators.

Adapted from data presented by Strauss, page 214. Industrial Gas Cleaning, Pergamon Press, 1975.

Mechanically aided separators. The theory of collection for mechanically aided separators is similar to that used in momentum separators. The velocity of the gas stream and the turn made by the gas stream are generated mechanically in a fan or other device. The high radial tip velocity of the moving mechanical surface and the momentum generated by the increased gas velocity move the particles to the perimeter of the moving surface. The particle concentration is increased in the outer portion of the fan and separated from the main gas flow by a secondary gas flow. The normal secondary flow is between 10 and 20 percent of the total system volume. Two types of mechanically aided separators are shown in Figure 4.2-13a.



SCROLL TYPE

COMPOUND SCROLL TYPE

Figure 4.2-13a. Types of mechanically aided separators.

Scroll-type collector drawing reprinted from: Stairmond, C. J. and Kelsey, R. N., Chemistry and Industry, pp. 1324, 1955. Compound Scroll-type drawing reprinted by permission of Buell Ltd., George St. Parade, Birmingham B3 1QQ

The theory of collection is not developed for collectors of this type, and the penetration curves are developed empirically. Figure 4.2-13b shows penetration curves for the scroll- and compound-scroll type collectors. The secondary collector may be a conventional centrifugal collector such as a cyclone.

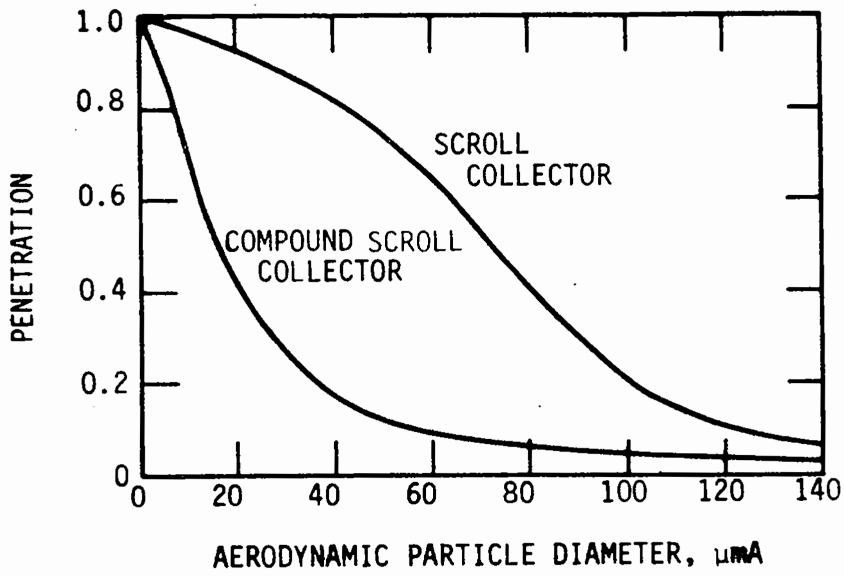


Figure 4.2-13b. Penetration curves for mechanically aided separators.

Reprinted from: Strauss, Industrial Gas Cleaning, Pergamon Press, page 265, 1975.

Cyclonic separators. The performance of cyclonic separators is dependent on particle size. Theoretical relationships have been based on two different parameters, the critical particle diameter and the 50 percent cut size diameter. The former is the smallest particle size collected with 100% collection efficiency (penetration of zero). Summaries of a number of these equations are presented by Calvert et al.[11] and Strauss.[7] Such equations provide only a general indication of whether a cyclone will be adequate for a specific application.

Theoretical models based on the 50 percent cut size have been developed by Lapple,[12] Leith and Licht,[13] and Kalen and Zenz.[14] Differences in the equations result primarily from the assumptions used to explain particle behavior with the cyclone. These and other approaches are described in detail in Strauss,[7] Crawford,[1] Licht,[15] and Theodore and Buonicore.[4]

The Leith and Licht model is based on the general concept of radial mixing within the cyclone cylinder due to a combination of turbulent mixing and particle bounce.

The dependence of the particle size-specific penetration, P_i, on cyclone design parameters and gas stream characteristics is presented in Equation 4.2-7, which was developed by Licht.[15]

$$P_i = e^{-2\left[\frac{KQ\rho_p\,(n+1)}{D^3 18\mu}\right]^{\frac{1}{2n+2}}\left[d_i^{\frac{1}{n+1}}\right]} \qquad \text{(Eq. 4.2-7)}$$

Parameters used in Equation 4.2-7 are defined in Equations 4.2-8 to 4.2-13. The factor, n, is a temperature-dependent parameter originally presented by Alexander.[16]

$$n = 1 - (T/283)^{0.3}[1 - 0.67\,(D)^{0.14}] \qquad \text{(Eq. 4.2-8)}$$

$$K = \frac{8[(V_s + 0.5V_{n\ell})/D^3]}{[H/D]^2\ [B/D]^2} \qquad \text{(Eq. 4.2-9)}$$

$$V_s = \frac{\pi}{4}\,[S - 0.5a][D^2 - D_a]^2 \qquad \text{(Eq. 4.2-10)}$$

$$V\ = \frac{\pi}{4}D^2(h-S) + \frac{\pi}{4}\left(\frac{\ell + S - h}{3}\right)D^2\left[1 + \frac{d}{D} + \frac{d^2}{2}\right] - \frac{\pi D_e^2\,\ell}{4} \qquad \text{(Eq. 4.2-11)}$$

$$d = D - \frac{(D-B)(S+\ell-h)}{H-h} \qquad \text{(Eq. 4.2-12)}$$

$$\ell = 2.3\,D_e\,(D^2/ab)^{0.33} \qquad \text{(Eq. 4.2-13)}$$

where S = height of outlet tube extension, m

a = height of inlet duct, m

D_e = diameter of outlet tube, m

D = diameter of cyclone cylinder, m

h = height of cyclone cylinder, m

ℓ = "natural length," m

H = height of cyclone and cone, m

B = diameter of cyclone cone outlet, m

b = width of cyclone inlet, m

ρ_p = particle density, kg/m^3

Q = gas flow rate, m^3/s

μ = gas viscosity, kg/m-s

P_i = penetration of a particle having an aerodynamic diameter of i, dimensionless

The Leith and Licht equations give a fractional penetration curve of the type shown in Figure 4.2-14. The cyclone dimensions and gas flow characteristics used in the calculation of this curve are presented in Reference 15.

Lapple's cyclone performance model involves the calculation of the particle cut diameter, d_{50}, using Equations 4.2-14 and 4.2-15

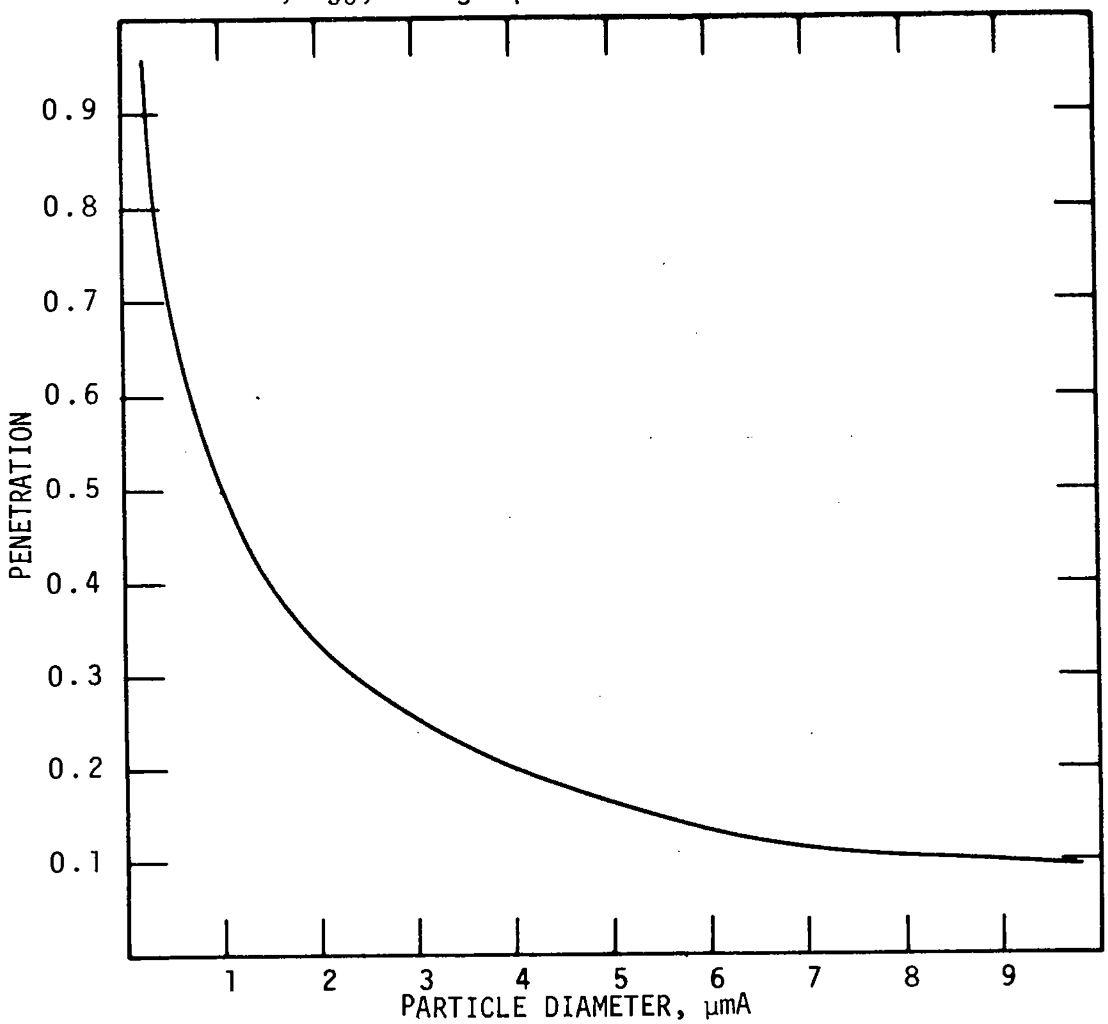


Figure 4.2-14. Penetration curve predicted by Leith and Licht approach.

Adapted from: D. Leith and W. Licht, American Institute of Chemical Engineers Symposia Series 68, 1972

$$d_{50} = 0.308\ [(9\ \mu_G B_c)/2\pi N_t v_i(\rho_p - \rho_G)]^{0.5} \qquad \text{(Eq. 4.2-14)}$$

$$N_t = \frac{(V/Q)}{\pi D}V \qquad \text{(Eq. 4.2-15)}$$

where d_{50} = particle diameter collected with 50% efficiency, μmA

μ_G = gas viscosity, kg/m-s

B_c = width of gas inlet, m

v_i = inlet gas velocity, m/s

ρ_p = particle density, kg/m³

ρ_G = gas density, kg/m³

N_t = effective number of gas turns, dimensionless

V = volume of cyclone, m³

Q = gas flow rate, m³/s

D = diameter of cyclone cylinder, m

Calculation of the volume of the cyclone and Equations 14 and 15 yield the d_{50}. This is a useful parameter for comparing various cyclones. If a fractional penetration curve is desired, the d_{50} can be used in conjunction with a generalized curve as shown in Figure 4.2-15 from Theodore and Buonicore.[4] A more detailed discussion of this approach is provided in the latter reference. Information concerning theoretical performance models is presented in Licht,[15] Theodore and Buonicore,[4] Kalen and Zenz,[14] and Theodore and DePaola.[17] The general relationship between particle penetration and cyclone parameters is summarized in Table 4.2-2.

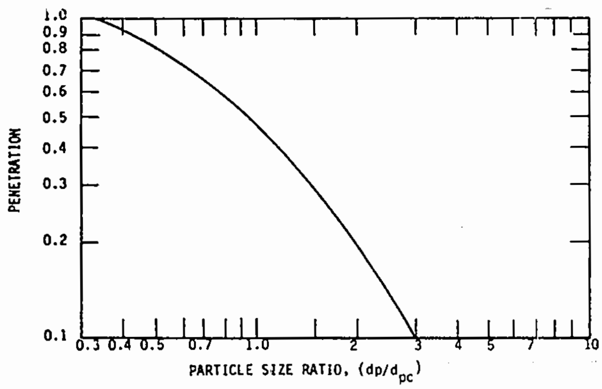


Figure 4.2-15. Cyclone penetration as a function of particle size ratio.

Adapted from: Theodore and Buonicore, Industrial Air Pollution Control Equipment for Particulates, CRC Press, 1976.

TABLE 4.2-2. EFFECTS OF OPERATING CONDITIONS ON CYCLONE PERFORMANCE

Variable	Relationship	Reference
Gas flow rate	$\frac{P_1}{P_2} = \left(\frac{Q_2}{Q_1}\right)^{0.5}$	Licht,[15] Theodore and Buonicore[4]
Particle density	$\frac{P_1}{P_2} = \left[\frac{(\rho_{p_2} - \rho_{g_2})}{(\rho_{p_1} \quad \rho_{g_1})}\right]^{0.5}$	Licht,[15] Theodore and Buonicore[4]
Gas viscosity	$\frac{P_1}{P_2} = \left(\frac{\mu_1}{\mu_2}\right)^{0.5}$	Licht,[15] Theodore and Buonicore[4]
Dust loading	$\frac{P_1}{P_2} = \left(\frac{C_2}{C_1}\right)^{0.182}$	Baxter[18]

The fractional efficiency of a cyclone system may be improved by reducing the cyclone diameter and using multiple cyclones to handle the gas flow. Penetration curves for several common multiple-cyclone tubes are shown in Figure 4.2-16.

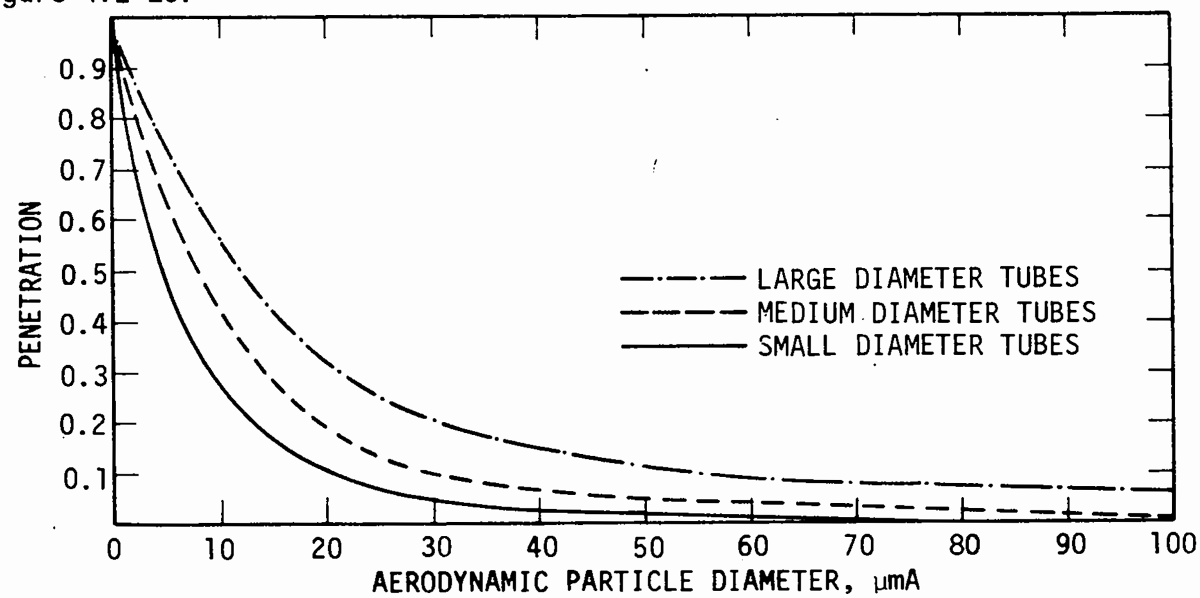


Figure 4.2-16. Penetration curves for multicyclone tubes of different diameter.

Adapted from: Theodore and Buonicore, Industrial Air Pollution Control Equipment for Particulates, CRC Press, page 129, 1976.

The overall penetration curve for a number of cyclones in parallel, such as in a multiple-cyclone tube bank, may differ from the efficiency of individual tubes because of interferences from the inlet and outlet, gas distribution, dust stratification, reentrainment from the hopper, inleakage, axial vane wear, plugging, and variation in pressure drop across individual tubes.

Axial inlet - axial discharge (double vortex) cyclones. The fundamental mechanisms involved in the double vortex cyclones have been discussed in detail by Schmidt;[19] however, theoretical models are not available. A general penetration curve prepared by Aerodyne Corporation is presented in Figure 4.2-17.

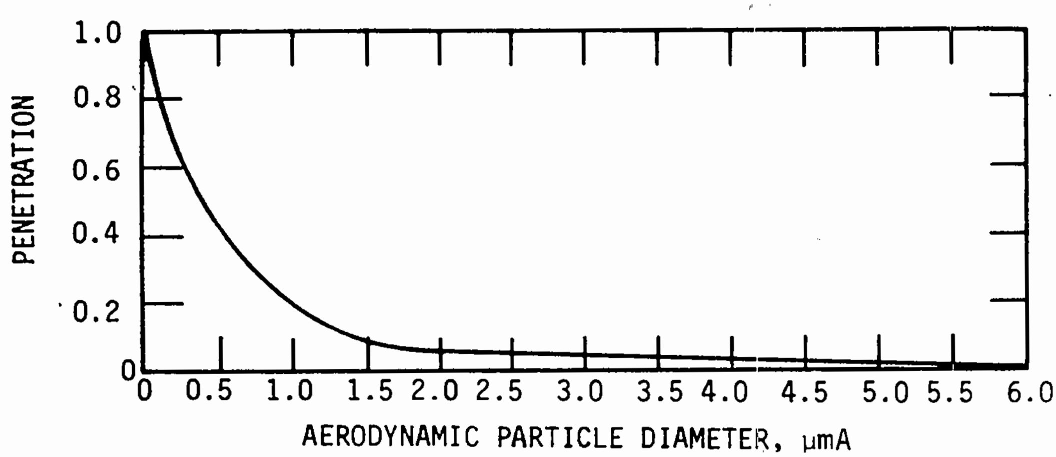


Figure 4.2-17. Penetration curve for double vortex cyclone.

Reprinted with permission of Aerodyne Corporation, Cleveland, Ohio.

The reduced penetration claimed in the <2-μmA size range may be partially due to reduced particle reentrainment resulting from particle bounce. Additional information is available in Klein.[20]

4.2.2.2 Static Pressure Drop. Typical cyclones have static pressure losses ranging from 0.25 to 1.5 kPa. A number of factors contribute to this, including the kinetic energy losses in the cyclone vortex, cyclone cylinder wall friction, and entry and exit duct functions. The kinetic energy losses are normally considered to be the dominant factor.

One common means to calculate static pressure drop, ΔS.P., is based on "inlet velocity heads." Licht[15] summarizes the basic approach in Equations 4.2-16 and 4.2-17. Equation 4.2-16 was originally developed by Shepard and Lapple.[21]

$$\Delta S.P. = 7.6 \times 10^{-6} \rho_G V_i^2 \ N_H \qquad \text{(Eq. 4.2-16)}$$

$$N_H = 16 \ a \ b/D_e^2 \qquad \text{(Eq. 4.2-17)}$$

where ΔS.P. = static pressure loss, m of H_2O

ρ_G = gas density, kg/m^3

V_i = gas inlet velocity, m/s

N_H = number of velocity heads

a = inlet duct width, m

b = inlet duct height, m

D_e = diameter of exit tube, m

This simple approach for single cyclones indicates that the static pressure is proportional to the square of the inlet velocity and is directly proportional to the inlet/outlet area ratio. Because of the dependence on gas inlet velocity, it follows that static pressure drop is proportional to the square of the gas flow rate. Other pressure drop equations share the gas-flow-rate squared dependence, but differ with respect to the cyclone dimensional factors taken into account. For more information on these approaches, see Strauss,[7] Theodore and Buonicore,[4] and Byers.[22]

4.2.3 Design of Mechanical Collectors

Proper design of mechanical collectors is necessary to ensure unit operation at optimum efficiency and to minimize malfunctions. This section addresses both the design needed to achieve desired penetration levels and the factors necessary for continuous compliance.

4.2.3.1 Settling Chambers. Proper design of settling chambers includes not only specifying the volume adequate for overall collection efficiency, but also ensuring uniform gas distribution and minimum turbulence.

A nonuniform gas distribution in the inlet can result in locally high velocities and nonuniform dust concentrations through the chamber. The high velocities lead to increased penetration of fine particulates. Gas distribution may be improved by the use of gradual turns in the ductwork, straightening vanes, and perforated plates.

The design must prevent air inleakage into the chamber and dust hopper. Inleakage increases turbulence, causes dust reentrainment, and prevents dust discharge from the hopper. Inleakage through the hopper can be prevented by use of a rotary air lock, flapper valve, or other means of sealing the dust discharge. Inleakage through the chamber shell can be prevented by use of proper welding practices and proper materials of construction. When a chamber is used to process a gas stream at high temperatures with high moisture content, the inleakage of cold air causes local gas quenching and condensation. The condensation can cause corrosion, dust buildup, and plugging of the hopper. The use of thermal insulation can reduce radiant heat loss and prevent operation below the dew point.

Materials of construction must provide extended life under conditions of corrosion and abrasion. The composition and gauge of materials should be specified on the basis of the expected composition of the gas stream. Access doors and cleanout doors should be included to allow inspection and cleanout of duct work, distribution vanes, and hoppers.

Since the large particles are separated at the front of the collectors, it is expected that the maximum weight and volume of material will accumulate near the collector inlet. The design must incorporate special access for frequent dust removal from this area to maintain operation. Normal instrumentation for settling chambers consists only of an indicator of differential static pressure. An increase in static pressure drop can indicate plugging of turning vanes or distribution plates.

4.2.3.2 Momentum Separators. The design of momentum separators must provide sufficient volume to allow settling of materials separated from the high-velocity gas stream and materials of construction hard enough to survive high abrasion.

As with all collectors, the design must include methods of sealing dust discharge from hoppers to prevent inleakage. The methods may include use of rotary air locks, flapper valves, or other positive sealing devices. Inleakage through the hopper or shell results in changes in the gas distribution, interferes with dust discharge, and may cause condensation or corrosion.

Because of the high velocities used to separate the particles from the gas stream and the impaction of these particles on surfaces that direct the gas flow, the materials of construction must have high abrasion resistance.

Access must be provided for inspection and cleanout of the gas passages and dust hoppers. The access must be large enough to allow the changing of surfaces subject to high abrasion such as liners or blast plates.

Normal instrumentation consists only of differential static pressure indicators. The plugging of gas passages or abrasion of baffle plates may be indicated by a shift in normal static pressure drop. Such effects, however, should be detected by visual inspection of the collector before a significant change in static pressure is noted.

4.2.3.3 Mechanically Aided Separators. Because of the high rotational speed of mechanically aided collectors, the major design considerations are abrasion and vibration. Because of the abrasion associated with removal of large particles, the design must include an impeller made of materials with high abrasive resistance. The inlet of the collector is designed to provide even wear of the impeller. If uneven wear occurs, the resulting imbalance could cause bearing or impeller failure.

The effects of abrasion and material buildup on the impeller are minimized by operating the units at low speeds (typically 400-800 rpm). Buildup of sticky or wet materials on the impeller may be reduced by a water spray in the inlet. The coating of water reduces adhesion of particles and acts as a wet fan.

The periodic sheeting of materials from the blade tips results in moderate vibration. The housing and structural support should be either spring-mounted or rigidly fixed to a substantial foundation, depending on ability to isolate the system from ductwork.

Since the mechanically aided collector acts as the prime air mover in the system, the air volume is affected by all of the normal variables that affect fans. The typical fan curve may not be applicable because of continuous changes in surface contour resulting from wear and material buildup.

Because of the constant change in operating conditions, the penetration curve is subject to change.

An increase in impeller weight caused by buildup can increase drive belt slippage and can increase brake horsepower. The design should allow for multiple drive belts or direct drive and high motor horsepower.

4.2.3.4 Cyclones.

Simple cyclones. The design of simple cyclones includes sizing of the cyclone to provide an inlet velocity that will ensure high separation efficiency without excessive turbulence. Typical values range between 10 and 25 m/s.[4] Turbulence at high inlet velocities results in abrasion of the cyclone wall and gas outlet duct. These areas can be reinforced by use of materials of extra hardness or thickness. Turbulence can be reduced by use of inlet configurations such as helical or involuted designs.

The design should use flush welds and should avoid components that increase roughness, such as rivets. Internal disturbances reduce efficiency by creating areas of turbulence and causing particles to bounce from the wall to the inner vortex. The design should also include methods of sealing the dust discharge and preventing gas inleakage, such as use of a rotary air lock, flapper valves, or other devices.

Multiple cyclones. The design of a multiple-cyclone system entails specification of the number of individual tubes needed to handle the gas volume without exceeding the maximum gas flow per tube. If the inlet velocity of the tube is excessive, the resulting turbulence increases penetration. At excessive inlet velocities abrasion also increases. In general, the maximum inlet velocity may be limited by the abrasiveness of the particles to be collected and by the abrasion resistance of inlet vanes.

The arrangement of the tube bank generally should be in a square matrix. The use of internal baffles in the inlet can allow a collector of shallow depth to be used without abnormal gas distribution across the width. Because of the possibility of static pressure differential across large tube banks and the resulting hopper short-circuiting, baffles should be included in the hopper or multiple hoppers should be provided.

Access should be provided both to clean and dirty collector plenums for dust cleanout, inspection, and replacement of tubes. The access doors should be large enough to permit safe entry and removal of tubes. Gasket materials used to seal tube assemblies, access doors, etc., should have long life at elevated temperatures. A major cause of failure of well-designed systems is gas penetration through weld gaps and gasket leaks from the dirty side to the clean side.

The collection hopper should be equipped with devices that provide positive sealing of the dust outlet, e.g., rotary valve, flapper valve, or other devices to prevent air inleakage. Air leakage can cause dust discharge, hopper bridging, and condensation.

The collector should be equipped with differential static pressure monitoring equipment to determine static pressure drop.

4.2.4 Operation and Maintenance of Mechanical Collectors

Even well-designed equipment can fail because of improper operation and inadequate maintenance. Despite the apparent simplicity of mechanical collectors, regular maintenance is necessary.

4.2.4.1 Settling Chambers. The most common failure mode of settling chambers is plugging of the chamber with collected dust. In simple collectors the plugging can result from hopper bridging or rotary air lock failure. In more complex collectors, such as Howard's settling chamber, plugging of the individual gas passages can occur. Such failures can be prevented or minimized by use of hopper level indicators or by continuous monitoring of the dust discharge. Scheduled internal inspection can determine areas of inleakage and condensation, both of which may cause hopper bridging.

4.2.4.2 Momentum Separators. The most common failure modes of momentum separators are hopper plugging and baffle plate erosion. Plugging of hoppers can be reduced by use of hopper level indicators. Erosion of baffle plates and collector shell can be reduced by the use of extra thickness in areas subject to abrasion. Periodic internal inspection of the collector is recommended to identify and correct areas of high abrasion and air inleakage.

4.2.4.3 Mechanically Aided Separators. The most common failure modes of mechanically aided separators are abrasion and structural disintegration.

The impact of an abrasive dust on impeller surfaces at high tip speeds causes rapid erosion. The impeller can become unbalanced; and if the unbalance is not corrected, structural failure can occur. The attachment of sticky or tacky particulate to the impeller can also cause vibration.

The use of vibration detectors and periodic external inspection can indicate impending failure from erosion or material buildup. Routine internal inspection of the impeller with removal of collected material can extend collector life.

4.2.4.4 Simple Cyclones. Simple cyclones fail most often from abrasion and plugging of the dust outlet tube. Abrasion occurs in areas opposite the gas inlet and in the lower areas of the cone. Wear can increase if inlet velocities are high (>25 m/s) and particles can erode the gas outlet tube. Internal roughness caused by poor welding or faulty fabrication can cause local turbulence, which increases erosion and particle bounce into the inner vortex. Plugging of the dust outlet tube can be reduced by use of a large diameter outlet tube and by proper sizing of the rotary air lock.

Routine internal inspection of the inlet duct and internal surfaces for areas of abnormal wear should be conducted to prevent shell failure. Liners and replaceable wear plates are recommended where abrasive dust is collected.

4.2.4.5 Multiple Cyclones. Factors which may contribute to reduced performance include erosion, plugging, corrosion, and hopper recirculation.

Hopper recirculation in reverse flow type systems occurs when tubes at the rear of the bank have a slightly lower static pressure drop. This can occur whenever flow distribution is nonideal or when the outlet tubes are shorter than those in the front[23,24] (a common design). In these cases a portion of the gas in the front tubes can pass out the bottom and then enter the discharge of tubes in the back rows.

Hopper recirculation can lead to substantially reduced collection efficiency.[24] Some of the ways to minimize this problem include segregating the hopper and equalizing the lengths of all discharge tubes.[23]

Ambient air inleakage into the hopper area can interfere with the dust discharge in the tubes and lead to increased emissions. These leaks may occur at hopper flanges, access hatches or through the solids discharge valves. Severe leakage on multicyclones serving combustion systems can be identified by measurement of the flue gas oxygen content before and after the collector.

Plugging of the gas inlet vanes leads to partial or total failure of individual tubes to establish an adequate vortex. Partial plugging allows dust penetration through the affected tube (Figure 4.2-17). Complete plugging results in an increased flow of gas through the remaining tubes and an increase in overall collector static pressure drop. Partial plugging of a significant number of tubes can cause variation in pressure drop from tube to tube, cause gas short circuiting through the dust hopper, and cause an increase in dust reentrainment at the tube dust outlet.

Plugging of outlet tubes or the solids discharge is common.[23] The latter is generally due to poor hopper discharge practices, which allow solids to accumulate to the bottom of the tubes.[23] According to Barrow,[25] a single plugged tube can reduce collection efficiency by as much as 25 percent.

Excessive gas velocities at the entrance of the multicyclone can lead to erosion of the outlet tubes. Once a small hole is created, the large differential static pressure between the inlet and outlet leads to very high gas velocities through the hole. Rapid erosion then leads to substantially reduced collection efficiency.

Corrosion in multicyclone collectors is usually minimized by avoiding operation at or near the acid vapor dewpoint.[23] In certain cases, insulating the units and ductworks leading to it may be advisable.

Regular inspection of the multicyclone should be performed to minimize the above problems. Static pressure taps should be installed on the inlet and outlet ducts so that the static pressure drop can be measured on a regular basis by either a portable gauge or a permanently mounted instrument. Because of the tendency of these taps to plug, they should be cleared before any measurements are attempted.

For units serving combustion sources, gas temperature and flue gas oxygen content should be measured on a routine basis. This value should be compared with typical values for the specific unit to identify deterioration of the unit and/or operation below the dewpoint.

Figure 4.2-18. Partial pluggage of multiple cyclone inlet vanes. (Courtesy of PEDCo Environmental, Inc.)

The rate of solids discharge should be checked frequently. Bridging of solids in the hopper, failure of the solids discharge valve, or severe internal problems may all be identified by this simple technique. All of these situations demand immediate attention.

At least once a year, internal inspections should be conducted after the unit has been purged by personnel qualified in proper confined-area-entry procedures. The internal inspection should identify plugging, erosion, and corrosion problems. In some cases it may be advisable to use tracers or smoke to identify gasket and weld leaks.

REFERENCES

1. Crawford, M. Air Pollution Control Theory, McGraw-Hill, Inc., New York. 1976, p. 236.

2. Sargent, G. Gas/Solid Separation. Chemical Engineering. 78(4):11-12. February 15, 1971.

3. Munson, J. S. Dry Mechanical Collectors. Chemical Engineering. 75(22):147-151. October 14, 1968.

4. Theodore, L., and A. J. Buonicore. Industrial Air Pollution Control Equipment, CRC Press, Cleveland, Ohio, 1976, p. 65.

5. Alden, J. L. Design of Industrial Exhaust System, 3rd ed. The Industrial Press, New York. 1959.

6. Jennings, R. F. J. Iron Steel Inst. 164:305. 1950.

7. Strauss, W. Industrial Gas Cleaning, 2nd ed. Pergamon Press. 1975, p. 213.

8. Stairmund, C. J. Trans Instr. Chem Engrs. 29:356. 1951.

9. Caplan, K. Mechanical Collectors. In: Air Pollution, Vol. III, 2nd ed. Stern, A., Editor. Academic Press. New York. 1968.

10. Aerodyne Development Corporation, Series "SV" Dust Collector, Bulletin No. 1275-SV.

11. Calvert, S., J. Goldschmidt, D. Leith, and D. Mehta. Wet Scrubber Handbook, Vol. I. U.S. EPA. Research Triangle Park, N.C. Publication No. EPA-R1-72-118a. 1972.

12. Air Pollution Engineering Manual. U.S. Environmental Protection Agency Publication, AP-40. Research Triangle Park, N.C. 1973. p. 95.

13. Leith, D., and W. Licht. A.I.Ch.E. Symposium Series. 68:196. November 26, 1979.

14. Kalen, B., and F. A. Zenz. A Theoretical-Empirical Approach to Saltation Velocity in Cyclone Design. The Ducon Company. Bulletin No. C-207. 1973.

15. Licht, W. Air Pollution Control Engineering. Marcel Dekker, Inc. 1980.

16. Alexander, R. Mck. Proc. Austral. Inst. of Min. and Met (N.S.). 152:202. November 3, 1949.

17. Theodore, L., and V. DePaola. Predicting Cyclone Efficiency. JAPCA, 30:1132-33. October 1980.

18. Baxter, W. In: Air Pollution, Vol. II, 3rd ed. Stern, A. Editor. Academic Press. New York. 1977.

19. Schmidt, K. R. Staub. 23:491-501. 1963.

20. Klein, H. Staub. 23:501-08. 1963.

21. Shepard, G. B., and C. E. Lapple. Ind. Eng. Chem. 31:972. 1939.

22. Byers, R. L. Gravitational and Dry Centrifugal Collectors and Air Pollution Control. In: Integrated Engineering Solution to Overall Pollution Control: Air, Water, and Solid Waste Problems. AICHE. New York. 1971.

23. Dey, A., J. Maloney, and J. D'Imperio. Inertial Separators. In: Air Pollution Engineering Manual. U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. AP-40. 1973. pp. 91-99.

24. National Asphalt Paving Association. The Maintenance and Operation of Exhaust Systems in the Hot Mix Batch Plant. Information Series 52, NAPA. Riverdale, MD. 1975.

25. Barrow, A. J., Jr. Particulate and SO_2 Control Technology for the Small and Medium Coal-Fired Boiler. Presented at the 1970 Industrial Coal Conference. Purdue University. October 7-8, 1970.

4.3 ELECTROSTATIC PRECIPITATORS

Electrostatic precipitators (ESP's) are high efficiency particulate collection devices applicable to a variety of source categories and gas conditions. Particle collection is done by application of electrical energy for particle charging and collection. Efficiencies of 99.9+ percent are possible, depending upon application, ESP design, and gas and particle characteristics.

4.3.1 Types of Electrostatic Precipitators

Electrostatic precipitators used for controlling particulate emissions may be placed in two general categories: dry and wet. The major difference is in the method by which the particulate is removed from the collection electrodes. Each of these categories of precipitators may be further subdivided on the basis of electrode geometry and application.[1] The dry ESP with plate-type collection electrodes and pyramidal hoppers is the predominant type in industrial applications. Regardless of the type of precipitator and its geometry, the particle capture is accomplished by electrostatic attraction.

4.3.1.1 Dry Precipitators. Examples of the industrial sources that heavily utilize dry ESP's for control of particulate emissions are utility boilers, cement kilns, kraft pulp recovery boilers, and metallurgical furnaces. Each industrial application requires different designs for the gas conditions and particulate characteristics.

The basic functions of an ESP are (1) to impart a charge to the particulate, (2) to collect the charged particulate on a surface of opposite polarity, (3) to remove the collected particulate from the collecting surface in a manner that minimizes reentrainment of the particulate into the gas stream, and (4) to discharge the collected particulate. Each dry ESP with horizontal gas flow must have a shell to enclose the collection and discharge electrode system, collection electrodes, discharge electrodes, a high-voltage transformer-rectifier for application of electrical power to the ESP, a system of rappers to remove particulate from the collection and discharge electrodes, and a system to remove the collected particulate from the precipitator proper. Figure 4.3-1 shows the basic features of a

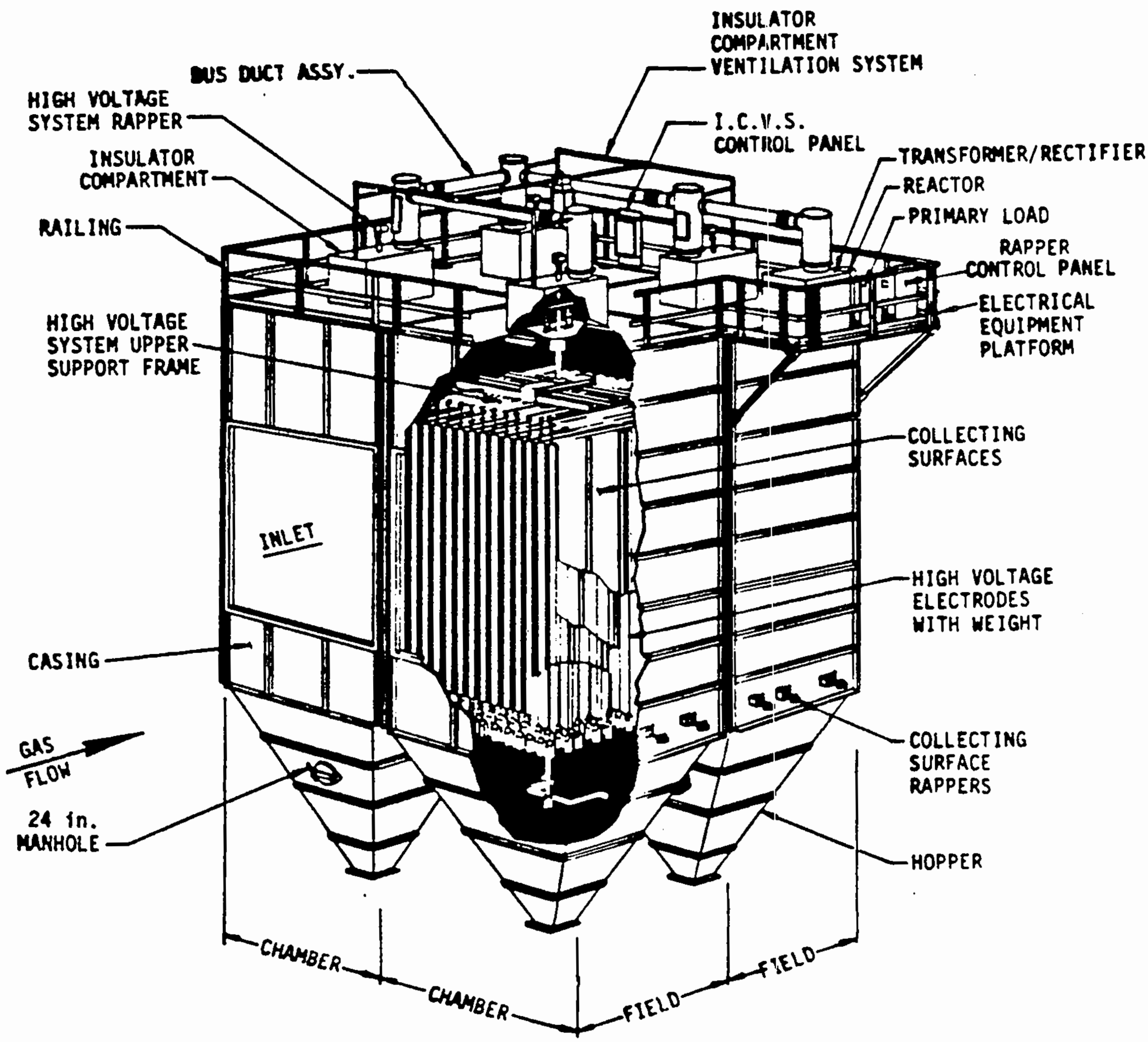


Figure 4.3-1. Typical ESP with insulator compartments (courtesy of Western Precipitation).[2]

weighted-wire discharge electrode ESP. Another type of design uses a rigid frame discharge electrodes mislead of weighted cones.

4.3.1.1.1 Precipitator housing or shell. Gases entering the precipitator are usually ducted so that gas velocities are high enough to prevent significant particulate fallout in the ductwork. These velocities (typically 20 to 35 m/s) are much too high for the ESP to capture the particles. Thus, the precipitator shell not only encloses the gas treatment area but also constitutes a large expansion volume in the ductwork to reduce gas velocity to between 1 to 2 m/s. This reduced velocity is necessary to allow sufficient residence time in the ESP for the particles to migrate to the collection electrodes and to avoid reentrainment to the gas stream.

The precipitator shell is typically made of carbon steel that is insulated to reduce corrosion of the shell. Doors are usually provided between each field to allow internal inspection and maintenance when the precipitator is off-line. Depending upon design and manufacturer, the precipitator may be equipped with a penthouse to house high-voltage insulators.

4.3.1.1.2 Discharge electrodes. Dry plate ESP's are of two types: weighted-wire and rigid-frame discharge electrode systems. The discharge electrode provides the charge to the particulate in the treatment zone. Weighted-wire designs (Figure 4.3-1) have dominated ESP service in the past. Wires are suspended from a high-voltage frame at the top of the electrical section, and shrouds are provided to reduce sparking between the wires and the end of the collection electrode. The weighted-wire design typically has a lower initial cost than rigid-frame designs, and closer spacings are allowed between collection electrodes and discharge electrodes. Rigid-frame designs, however, tend to provide lower maintenance requirements.

Both discharge electrode configurations have excellent collection capability. The low initial cost of a weighted-wire design is typically offset by high maintenance costs caused partially by wire breakage. The reverse is true for rigid-frame designs for which the high initial costs are usually offset by low maintenance costs. Warping of the discharge electrode frame because of wide thermal swings is generally not a problem with a properly designed unit. Electrically, both designs are capable of delivering similar power levels to the ESP for particulate collection. Generally, the rigid-frame design operates at higher voltages and lower current densities than the weighted-wire designs in a given application because of the wider discharge electrode to collection electrode spacing. These voltage-current characteristics may be better suited to collection of high-resistivity dusts.

4.3.1.1.3 Collection electrodes. The collection electrodes usually consist of a plate with stiffeners to provide support. Some manufacturers incorporate baffles (doubling as plate stiffeners) to provide regions of low gas turbulence that enhance particulate capture. The charged particles that migrate across the gas stream under the force of electrostatic attraction build up a layer of dust on the collection electrodes (plates).

4.3.1.1.4 High voltage transformer-rectifier (T-R). Operation of the ESP depends upon electrical power being supplied by high-voltage transformer-rectifiers (T-R). The function of the T-R set is to convert a low-voltage AC power to high-voltage DC. In most industrial applications the voltage applied is DC negative (negative corona) because higher power can be applied to the ESP at lower sparking values than is possible with positive corona units. Typically, a silicon-controlled-rectifier (SCR) circuit controls precipitator current "phase," and the high-voltage power supply includes an automatic control unit to control delivery of optimum voltage-current performance. Most modern ESP's also include linear reactors to modify the current waveforms and provide stability during sparking.

Most ESP's have a number of T-R sets; the number is determined by the manufacturer's preference in conjunction with the desired collection efficiency, degree of sectionalization, and degree of redundancy needed. The voltage and current ratings of the T-R's must be matched to the application, electrode geometry, and gas and particulate characteristics. Typically, input voltage is 460 V, three-phase, 60 Hz AC with an output voltage between 45 and 70 kV DC. The maximum rated current output of the T-R sets is usually in the range of 250 to 1500 milliamperes.

4.3.1.1.5 Insulators. Insulators are needed to prevent grounding of the high-voltage power supply system with the precipitator shell. Insulators are often made of a ceramic material selected for its high dielectric strength and resistance to most components in the gases to which it may be exposed. Insulators are used where the high-voltage supply penetrates the precipitator shell and is connected with the discharge electrode system and wherever the high-voltage system comes close to the precipitator shell or plates.

4.3.1.1.6 Rappers. For dry ESP's, some version of rapping must be used to remove particulate from collection surfaces. Rapper types include electric vibrators and gravity impact hammers. Rappers are provided for both the collection plates and discharge electrodes. Excessive dust buildup in the precipitator will degrade the performance of the precipitator and is usually evidenced by reduced power to the precipitator.

The number of rappers necessary for effective cleaning depends upon the type of rapper, the ESP configuration, and other design considerations. Each installation requires fine-tuning of both rapper intensity and rapping frequencies to minimize reentrainment of dust. The rapping intensity depends upon the particulate characteristics and the amount of collection area and discharge electrode to be cleaned per rapper. Rapping frequency generally decreases as the gas travels from inlet to the outlet of the ESP. It should be noted that excessive rapping can degrade ESP performance as much as insufficient or ineffective rapping.

4.3.1.1.7 Solids discharge. Pyramidal hoppers are generally used for collecting particulate. Discharge from hoppers may be accomplished by means of screw conveyors, drag conveyors, or pneumatic conveying systems. In the pulp and paper industry flat bottom, tile-lined precipitators that utilize drag conveyors are common on recovery boilers. Solids discharge can represent a significant problem in the operation of an ESP in that excessive buildup of material can cause an electrical shortage or misalignment of ESP internal components.

4.3.1.1.8 Gas distribution equipment. Effective utilization of electrical energy supplied to the ESP depends upon well-balanced air flow across the ESP. In new installations the requirements for extensive gas turning vanes, because of sharp bends in ductwork, can be reduced. Retrofitted ESP's, however, can present problems because of space limitations requiring sharp bends in the ductwork immediately before and after the precipitator. Gas turning vanes and some type of diffusion plate (e.g., perforated plates) are typically utilized to balance the gas flow.

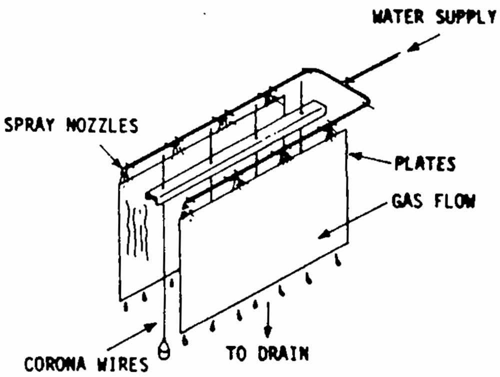
4.3.1.2 Wet Precipitators. Wet precipitators are used primarily in the metallurgical industry, usually operating below 75°C. Until the late 1960's their use was restricted mostly to acid mist, coke oven off-gas, blast furnace, and detarring applications. Their use in other areas is rapidly increasing with the need for increased control efficiencies. The new applications include sources with sticky and corrosive emissions. Because of inherent temperature range limitations, wet ESP's are not used for boiler installations.

The fundamental difference between a wet and a dry ESP is that a thin film of liquid flows over the collection plates of a wet ESP to wash off the collected particulates. In some cases, the liquid is also sprayed in the gas flow passages to provide cooling, conditioning, or a scrubbing action. When the liquid spray is used, it is precipitated with the particles, providing a secondary means of wetting the plates. Three different wet ESP configurations are shown in Figure 4.3-2.

4.3.1.2.1 Plate-type (horizontal flow). The effluent gas stream is usually preconditioned to reduce temperature and achieve saturation. As the gas enters the inlet nozzle, its velocity decreases because of the diverging cross section. At this point, additional sprays may be used to create good mixing of water, dust, and gas as well as to ensure complete saturation before the gas enters the electrostatic field. Baffles are often used to achieve good velocity distribution across the inlet of the ESP.

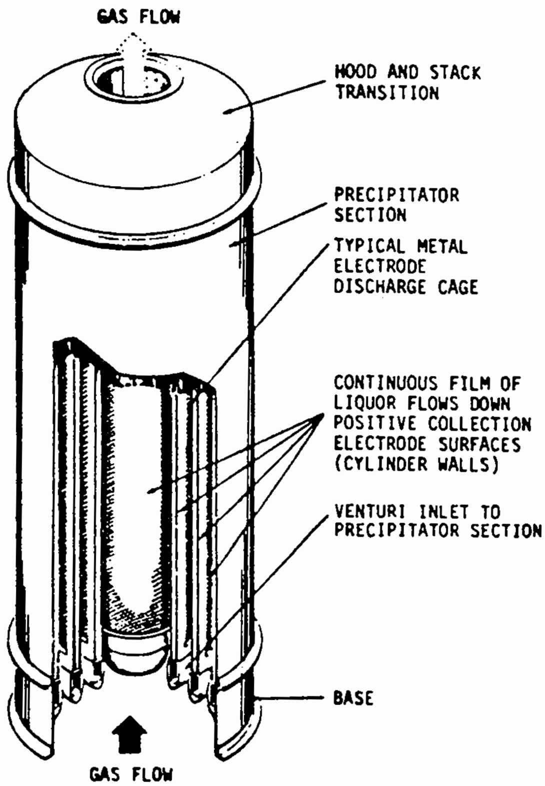
Within the charging section, water is sprayed near the top of the plates in the form of finely divided drops, which become electrically charged and are attracted to the plates, coating them evenly. Simultaneously, solid particles are charged; they "migrate" and become attached to the plates. Since the water film is moving downward by gravity on both the collecting and discharge electrodes, the particles are captured in the water film, which is disposed of from the bottom of the precipitator in the form of slurry.

4.3.1.2.2 Concentric-plate. The concentric-plate ESP consists of an integral tangential prescrubbing inlet chamber followed by a vertical wetted-wall concentric-ring ESP chamber.[3,4] Concentric cylindrical collection electrodes are wetted by fluids dispensed at the top surface of the collection electrode system. The discharge electrode system is made of expanded



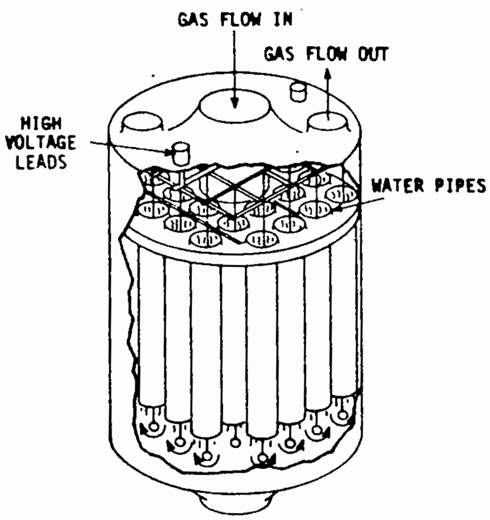
A. Plate type (horizontal flow)

Reprinted with permission of Academic Press. Stern, Arthur C., editor. AIR POLLUTION, 3rd edition, Vol. IV. 1977.



B. Concentric plate type

Reprinted with permission of Academic Press. Stern, Arthur C., editor. AIR POLLUTION, 3rd edition, Vol. IV. 1977.



C. Conventional pipe type

Courtesy of the McILvaine Co., THE ELECTROSTATIC PRECIPITATOR MANUAL.

Figure 4.3-2. Three types of wet ESP's.

metal with uniformly distributed corona points on the mesh background. This system is intended to combine the high, nearly uniform, electric field associated with a parallel plate system and the nearly uniform distribution of corona current density associated with closely spaced corona points. Higher gas flows can be handled by adding concentric electrode systems and by increasing the length of each electrode.

4.3.1.2.3 Conventional pipe-type. This system consists of vertical collecting pipes, each containing a discharge electrode (wire-type), which is attached to the upper framework and held taut by a cast-iron weight at the bottom. A lower steadying frame keeps the weights and thus the wires in position.

The upper frame is suspended from the high-voltage insulators housed in the insulator compartments, which are located on top of the precipitator shell (casing). Heating and ventilating systems help to prevent accumulation of moisture and dust in the insulator compartments.

The washing system usually consists of internal nozzles located at the top of the plates.[5] At specified intervals, the tubes are washed thoroughly. During the washing, the louver damper to the exhaust fan is closed to prevent carryover of droplets.

4.3.1.3 Two-stage Precipitators. The two-stage ESP was originally designed to purify air and is used in conjunction with air-conditioning systems. Cleaning of incoming air at hospitals and at industrial and commercial installations is a typical application. As an industrial particulate collector, the device is used for control of liquid particles discharged from such sources as meat smoke-houses, asphalt paper saturators, pipe coating machines, and high-speed grinding machines.

Two-stage ESP's are limited almost entirely to the collection of liquid particles that will drain readily from collection plates. Two-stage precipitators cannot control solid or sticky materials, and become ineffective if particle concentrations exceed 1.0 g/m^3.

4.3.2 Operating Principles of Electrostatic Precipitators

4.3.2.1 Basic Processes. The three basic processes involved in electrostatic precipitation are (1) the transfer of an electric charge to suspended particles in the gas stream, (2) the establishment of an electric field for removing the particles to a suitable collecting electrode, and (3) the removal of the particle layers from the precipitator (Figure 4.3-3).

4.3.2.1.1 Corona generation. As the high-voltage DC current passes through the discharge wire, it produces an electrical corona, which can be defined as an ionization of gas molecules by electron collisions in regions of high field strength near the discharge wire.[6] The strength of the electric field varies inversely with the distance from the discharge wire.

Three sources of electrons are used to initiate the so called "avalanche" of collisions (1) naturally occurring ionizing radiation, (2) photoionization because of the corona glow, and (3) in high-temperature applications, thermal ionization at the electrode surface.[6] These electrons and positive ions as well, move under the influence of an electric field and carry charges, but the current generated from the flow of these carriers is too low to be of significance. Under the influence of sufficiently high voltage, these free electrons are accelerated to a velocity high enough that collision with a gas molecule will break an electron loose from the outer shell of the molecule, creating a positive ion and another free electron.[7] This phenomenon is repeated many times, thus the name "avalanche." The end result is a large accumulation of positive ions and negative electrons in the region of the corona.

The corona can be either positive or negative; but the negative corona is used in most industrial precipitators since it has inherently superior electrical characteristics that enhance collection efficiency under most operating conditions.

4.3.2.1.2 Electric field. The electric field results from application of high voltage to the ESP discharge electrodes, and the strength of this electric field is a critical factor in determining ESP performance. Space charge effects from charged particles and gas ions may interfere with generation of the corona and reduce the strength of the electric field. The space charge effect is often seen in the inlet fields of an ESP where particulate concentration is the highest. From a practical standpoint, the strength or magnitude of the electric field is an indication of the effectiveness of an ESP. The magnitude of the electric field can be mathematically determined by use of derivations of Poisson's equations including charge carriers and their mobilities.[7]

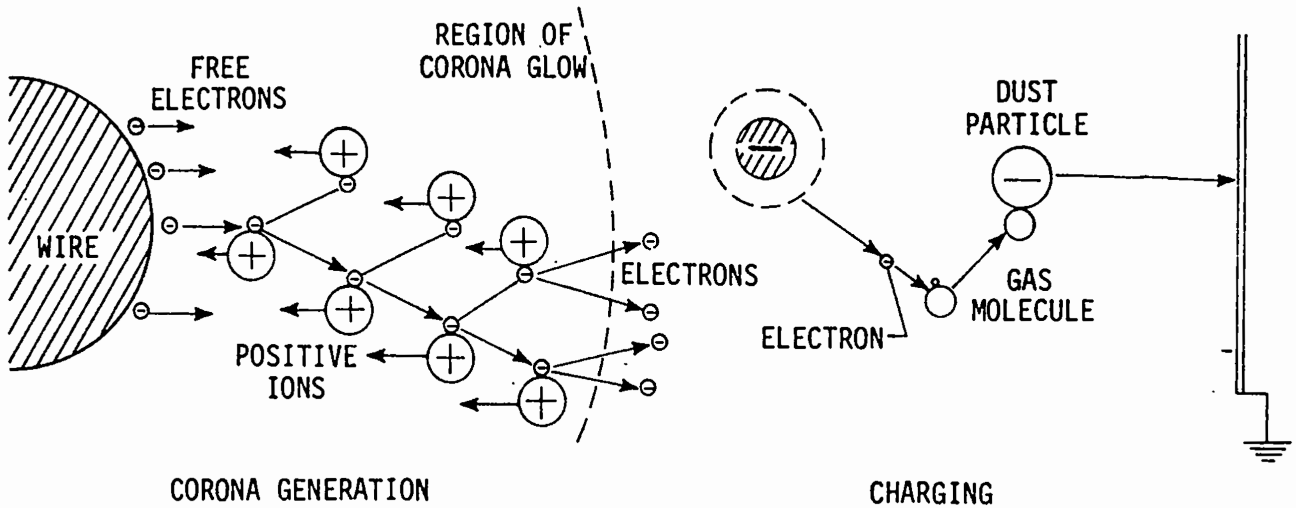


Figure 4.3-3. Basic processes involved in electrostatic precipitation.[7]
(Oglesby, Sabert Jr., "Electrostatic Precipitation" SRI Bulletin/Winter 1971.)

Courtesy of Southern Research Institute.

4.3.2.1.3 Charging mechanisms. Particle charging and subsequent collection take place in the region between the boundary of the corona glow and the collection electrode, where gas particles are subject to the generation of negative ions from the corona process. Charging is generally done by field and diffusion mechanisms. The dominant mechanism varies with particle size.

In field charging, ions from the corona are driven onto the particles by the electric field. As the ions continue to impinge on a dust particle, the charge on it increases until the local field developed by the charge on the particle causes such distortion of the electric field lines that they no longer intercept the particle, and no further charging takes place. This is the dominant mechanism for particles larger than about 0.5 μmA.

The time required for a particle to reach its saturation charge varies proportionally to the ion density in the region where charging takes place. Under normal conditions with sustained high-current levels, charging times are only a few milliseconds. Limitation of current because of high resistivity or other factors can lengthen charging times significantly and cause the particles to travel several meters through the precipitator before saturation charge is approached.

The waveform of the secondary voltage can further affect the charging times. The rectified unfiltered voltage has peaks occurring at regular intervals, which match the frequency of the primary voltage. Thus, the electric field varies with time, and the dust particles in the interelectrode region are subject to time-varying fields. The particle charging is interrupted for that portion of the cycle during which the charge on the particle exceeds that corresponding to the saturation charge for the electric field existing at the time. This further lengthens the charging times and, in the case of high-resistivity dust, degrades precipitator performance.[7]

Diffusion charging is associated with ion attachment resulting from random thermal motion; this is the dominant charging mechanism for particles below about 0.2 μmA. As with field charging, diffusion charging is influenced by the magnitude of the electric field, since ion movement is governed by electrical as well as diffusional forces. Neglecting electrical forces, an explanation of diffusion charging is that the thermal motion of molecules causes them to diffuse through a gas and contact the particles. The charging rate decreases as a particle acquires a charge and repels additional gas ions, but charging continues to a certain extent because there is no theoretical saturation or limiting charge other than the limit imposed by the field emission of electrons. This is because the distribution of thermal energy ions will always overcome the repulsion of the dust particle.[7]

The particle size range of about 0.2 to 0.5 μmA is a transitional region in which both mechanisms of charging are present but neither is dominant. Fractional efficiency test data for precipitators have shown reduced collection efficiency in this transitional size range, where diffusion and field charging overlap.

A more comprehensive theory[8] has been derived that analyzes the diffusion and field charging mechanisms simultaneously. The ion density distribution near a particle is determined in terms of the local electric field, and the rate at which ions reach the particle due to their thermal velocities is calculated statistically. A computer is used to calculate the theoretical charging rate, since it cannot be expressed in closed algebraic form. Results of this work indicate that the total charge accumulated by a particle is strongly dependent on the electric field strength, the diameter of the particle, the numerical density of the ions, and the residence time of the particle in the charging region. Other variables cited that can have a significant effect on particle charging rates are the gas temperature, electrical mobility of the ions in the gas, and the dielectric constant of the particulate material.

Sufficient rapping force must be applied to produce a rapid acceleration perpendicular to the gas flow so that the dust shears off the plate. Sproull[9] indicates that rapping is optimum if the dust layer slides down the plate vertically after each rap, making its way down the plate in the discrete steps until it finally reaches the hopper.

With a tenacious dust that adheres stubbornly to the plate, vibrations can be induced perpendicularly to the gas flow direction, in addition to the necessary shear action, resulting in a scattering of the agglomerate and subsequent reentrainment of relatively large fractions of the dust. In general, the dust should be allowed to fall freely off the plate, as sometimes occurs with high-resistivity dust when rapping is done with "power off." The other extreme is with low-resistivity dust, whose reentrainment can be caused by only a light rap.

Recent studies have investigated reentrainment caused by rapping in terms of the percentage of material reentrained and its particle size distribution.[10,11] One report describes the testing of six full-scale ESP installations. Losses from rapping ranged from over 80 percent of the total mass emissions from one hot-side unit to 30 percent of emissions from cold-side units. The losses consist mostly of relatively large particles, primarily those larger than 2.0 μmA in diameter. Tests of a pilot-scale precipitator showed that rapping emissions decreased as time between raps was increased.[3]

The intensity and frequency of rapping are usually greatest at the inlet sections, decreasing as the gas moves through the ESP. The outlet section is usually rapped only lightly, since the reentrained dust is not recollected. The visible puffs that often appear as a result of rapping can be used with a transmissometer to optimize the frequency and intensity of rapping for each section of the ESP.

4.3.2.1.4 Important process parameters influencing ESP performance. The process parameters that most influence the design and operation of ESP's are the particle properties such as resistivity and particle size distribution, and gas properties such as process temperature and flow. Once these factors are determined, the designer can estimate the size of the ESP needed to meet applicable emission regulations.

Corona current flows through the collected dust layer to reach the collection electrode.[1] With dry ESP's, high resistivity affects ESP efficiency by limiting the current and voltage. If electrodes are clean, the voltage can be increased until a sparking condition is reached. The maximum voltage is determined principally by the gas composition and ESP dimensions. When dust is deposited on the collection electrode, however, the voltage at which sparking occurs is reduced because of the increased electric field at the dust surface. As dust resistivities increase, the voltage at which sparking occurs decreases. At values of resistivity above approximately 10^{12} ohm-cm, the voltage must be reduced so that sparks will not propagate across the interelectrode space. At very low values of current and voltage, dust breakdown can occur. This can result in a back corona in which positive ions form and flow back toward the discharge electrode, neutralizing the negative charge previously applied and thereby limiting ESP performance.

In addition to reducing the performance of an ESP, high-resistivity dust can cling more tenaciously to collection electrodes than particles with intermediate resistivity. A much greater rapping acceleration must then be applied to the electrode to remove the dust layer. This can cause severe reentrainment or damage to a precipitator that is not designed to withstand such high acceleration.

Particle resistivity depends primarily on the chemical composition of the ash, the ambient flue gas temperature, and the amounts of water vapor and SO_3 in the flue gas.[12] At low temperatures <250°C, current conduction occurs principally along the surface layer of the dust and is related to the absorption of water vapor and other conditioning agents in the flue gas. For fly ash, resistivity is primarily related in an inverse manner to the amount of SO_3 and moisture in the flue gas. Burning of low-sulfur coal releases smaller amounts of SO_2, which is oxidized to SO_3. A higher-resistivity fly ash results, except at temperatures below about 250°C, where significant amounts of SO_3 are absorbed onto the fly ash particles.

At elevated temperatures >250°C, conduction takes place primarily through the bulk of the material, and resistivity depends on the chemical composition of the material. For fly ash at temperatures above 250°C resistivity is generally below about 10^{10} ohm-cm. Resistivity has been shown to decrease with increasing amounts of sodium, lithium, and iron.[13]

The range of operation of cold-side fly ash precipitators is 110° to 200°C, a range in which conduction takes place by a combination of the surface and bulk mechanisms and resistivity of the ash is highest. Figure 4.3-4 illustrates this relationship.

4.3.2.1.5 <u>ESP performance as a function of particle size</u>. The performance of an ESP varies considerably with changes in the particle size distribution. Particles from 0.1 to 1.0 μmA are the most difficult for an ESP to collect. Usually, the greatest penetration through an ESP is by particles 0.2 to 0.4 μmA (Figure 4.3-5). This penetration is probably caused by a transition from field charging to diffusion charging.

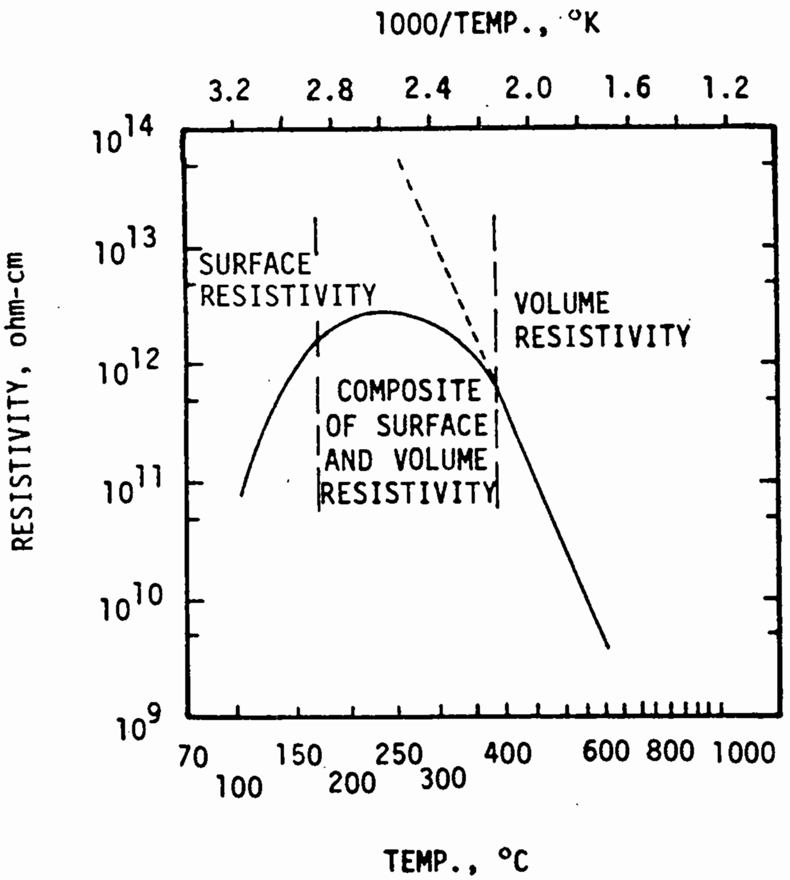


Figure 4.3-4. Typical temperature-resistivity relationship, (reprinted with permission of Academic Press. Stern, Arthur C., editor. AIR POLLUTION, 3rd edition, Volume IV. 1977).[7]

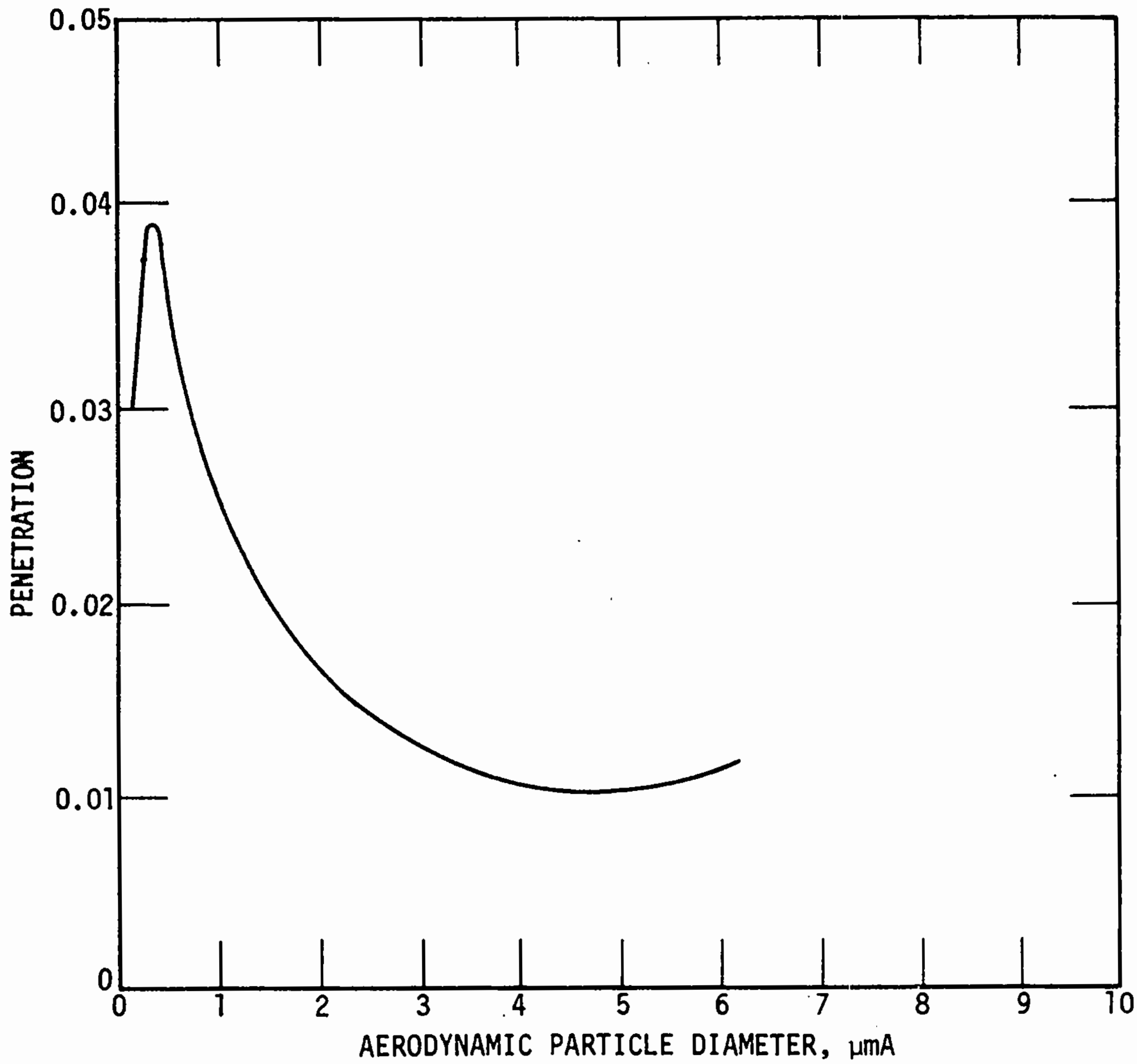


Figure 4.3-5. Penetration as a function of particle size for an ESP on a kraft pulp mill recovery boiler.[9]

Another problem posed by particles <1 μmA in diameter is the reduction in operation current associated with the electrical space charge of these fine particles. Introducing large quantities of fine particles at the inlet of the ESP can increase the electric field at the collecting plate, weaken the field near the discharge electrode, and suppress corona generation. This is known as corona quenching; it occurs when many incoming fine particulates acquire the same negative charge as the ions producing the charge, resulting in an electrical repulsion that tends to reduce operating current.

Performance as a function of particle size has been measured at many installations and has been the subject of computer modeling. Probably the best known and most versatile model is the EPA-Southern Research Institute Mathematical Model.[14] This model can be used for sizing and troubleshooting ESP's as well as for predicting penetration.

The effects of gas velocity distribution, mass entrainment, and gas sneakage on penetration can also be modeled. The following descriptions of the EPA-SoRI model is excerpted from Ensor et al.[15] Computations are based on the Deutsch equation. The migration velocity for particles of a given diameter is assumed to be constant over the collection area. The efficiency is calculated for each particle size over an incremental length of the precipitator. The incremental lengths must be sufficiently small to assure a constant electric field and particle charge. The total efficiency is integrated over each particle size over the total length of the ESP. The calculation involves an iterative solution based on an initial estimate of the total collection efficiency. Empirical corrections to the migration velocities for each particle diameter are used to verify the model. The space charge due to particulates is calculated in order to determine the reduced free ion density used to obtain the particle charge. The electrode spacing and applied voltage are used to calculate the electric field migration velocity. The nonideal behavior created by gas velocity distribution is determined empirically. The correction factor F is determined using this relationship:

$$F = 1 + 0.77\,\sigma^{1.786} + 0.0755\,\sigma\,\ell n\left(\frac{1}{1-\eta}\right) \qquad \text{(Eq. 4.3-1)}$$

where

σ = the normalized standard deviation of the gas distribution

η = the ideal collection efficiency.

The nonideal penetration is then calculated by:

$$P_t = \exp\left(-\frac{k}{f}\right) \qquad \text{(Eq. 4.3-2)}$$

where

P = penetration

k = constant predicted under ideal conditions by:

$$k = \ell n \left(\frac{1}{1 - \eta}\right) \qquad \text{(Eq. 4.3-3)}$$

Gas sneakage is another factor that can deteriorate ESP performance when gas bypasses the electrified areas by flowing through the hopper or through the high-voltage insulation space. A correction factor, B, analogous to the gas flow quality factor, F, can be used as a divisor for the migration velocity in the exponential argument of the Deutsch equation.

$$B = \frac{\ell n\,(1 - \eta)}{N_s\ \ell n[S_\eta + (1 - S_\eta)(1 - \eta)^{-N_s}]} \qquad \text{(Eq. 4.3-4)}$$

where

N_s = number of baffled sections

S_η = fractional amount of gas sneakage per section.

The model assumes that perfect mixing follows each baffled section. This model also considers the effects of rapping reentrainment on collection efficiency. It is assumed that the fraction of material that is reentrained does not vary with particle size or position and that the reentrained material is perfectly mixed in the gas stream after rapping. The effect on penetration is determined by the empirical relationships:

$$Y_1 = (0.155)\ X^{0.905} \text{ -- cold-side ESP}$$

$$Y_2 = (0.618)\ X^{0.894} \text{ -- hot-side ESP}$$

Y is the rapping emissions and X is the mass removed by the last electrical section; units are mg/DNm³.

Efficiencies with no plate rapping are used by the model to determine the mass removed by the last electric particle field. A log-normal approximation was used for particle size of the rapping emissions based on data from six different ESP field tests.

Figure 4.3-6 presents a comparison of data from the EPA-SoRI model with test data from the George Neal No. 3 ESP, operating on a low-sulfur pulverized-coal-fired boiler.[15] Best agreement comes with $\sigma = 0.6$, $S_\eta = 0.1$, and a rapping mass median diameter of 6 μmA. The curves do not match, however, at the low or high particle size range. The ideal values for velocity distribution and sneakage are believed to be higher than normal for a modern ESP and more the actual occurrence at the George Neal plant. Back corona was not included in the model, and this is believed to be the cause of most of the performance degradation. The results from this ESP were unusual in that the curves for penetration versus particle diameter showed a double peak in penetration, one at about 0.2 μmA and the other at about 1 μmA. Also, a major limitation of the model was the use of correction factors for nonideal conditions, which were unobtainable under normal plant operating conditions. For example, the gas velocity distribution is often obtained with velocity traverses with the boiler and ESP off and the draft fans operating. Thus, the comparison of the field data with data from the theoretical model was qualitative rather than quantitative.[15]

Some ESP manufacturers also have developed models for use in sizing precipitators. An example is a Research Cottrell (RC) model used to predict penetration of particulate through an ESP as a function of particle size. Although much simpler than the EPA-SoRI model, it includes many of the same concepts in calculating penetration as a function of particle size.

Predicted penetration as a function of particle size by the RC model is presented in Figure 4.3-7, for a cold-side ESP on a pulverized-coal-fired boiler. The computer model shows the expected maximum penetration in the 0.2 to 0.4 μmA size range. Comparison of the computer model with test data shows an excellent correlation, as indicated in Figure 4.3-8.

The RC model has been modified in more recent publications[16] to include a reentrainment factor, which can be used to estimate emissions due to rapping reentrainment at sources such as bark/fossil-fuel-fired boilers. Limitations of this rapping reentrainment factor are similar to the ones in the EPA-SoRI model: (1) overall migration velocity remains constant, (2) the fraction of material reentrained remains constant for different particle

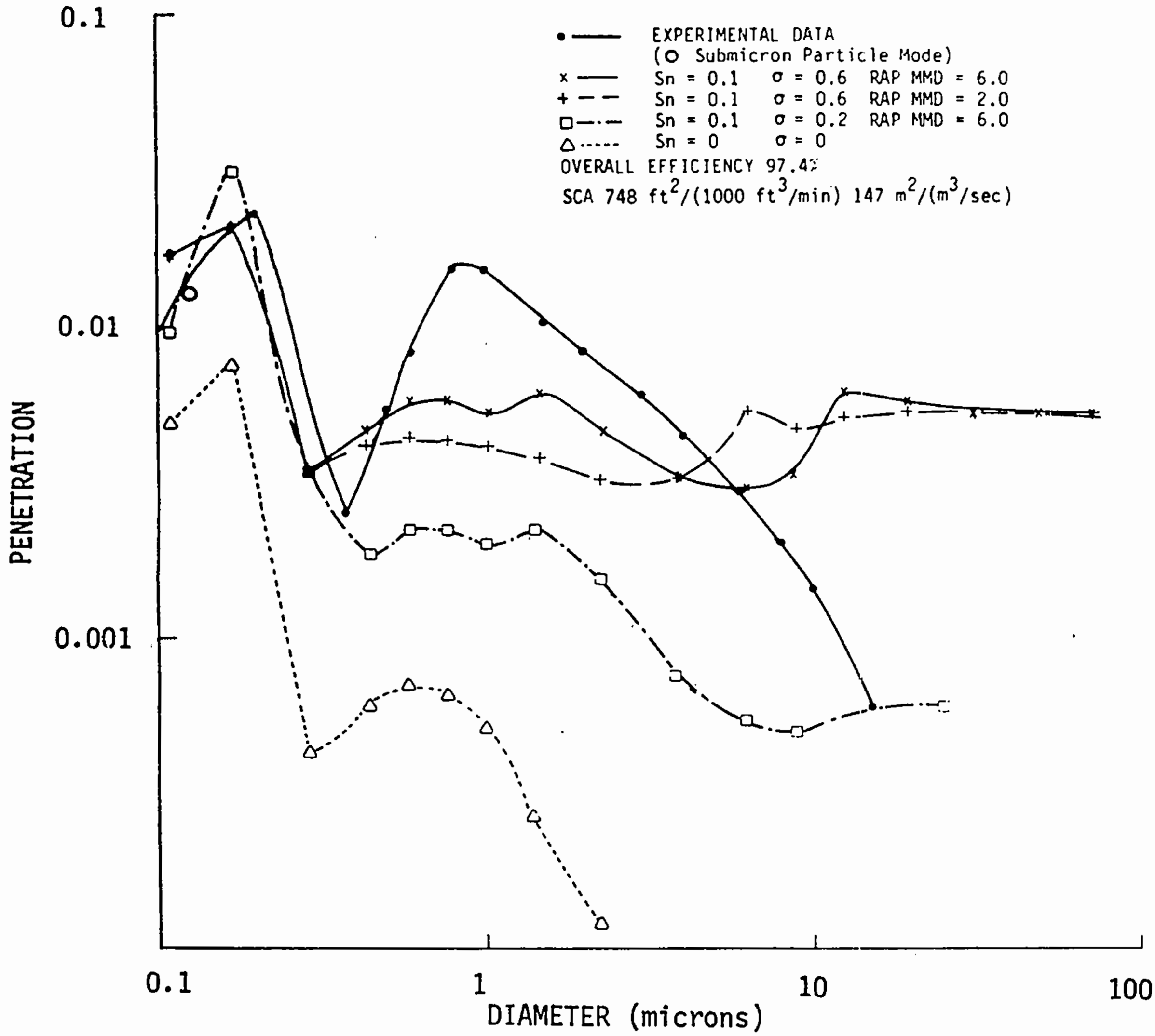


Figure 4.3-6. Comparison of experimental penetration as a function of particle diameter to the McDonald (1978) computer model under normal SCA conditions.[16]

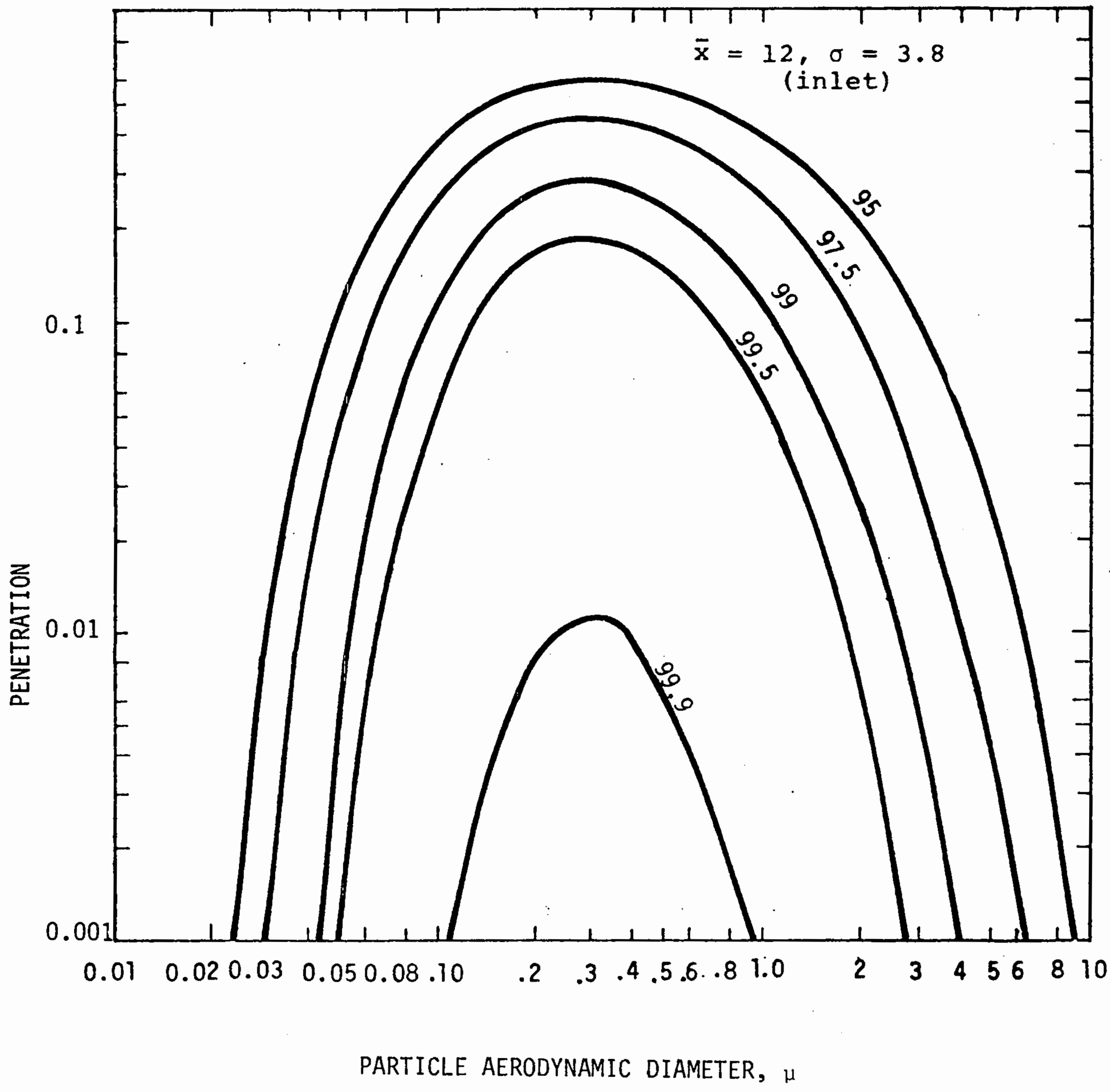


Figure 4.3-7. Penetration, pulverized-coal-fired boiler (cold-side ESP).[2]

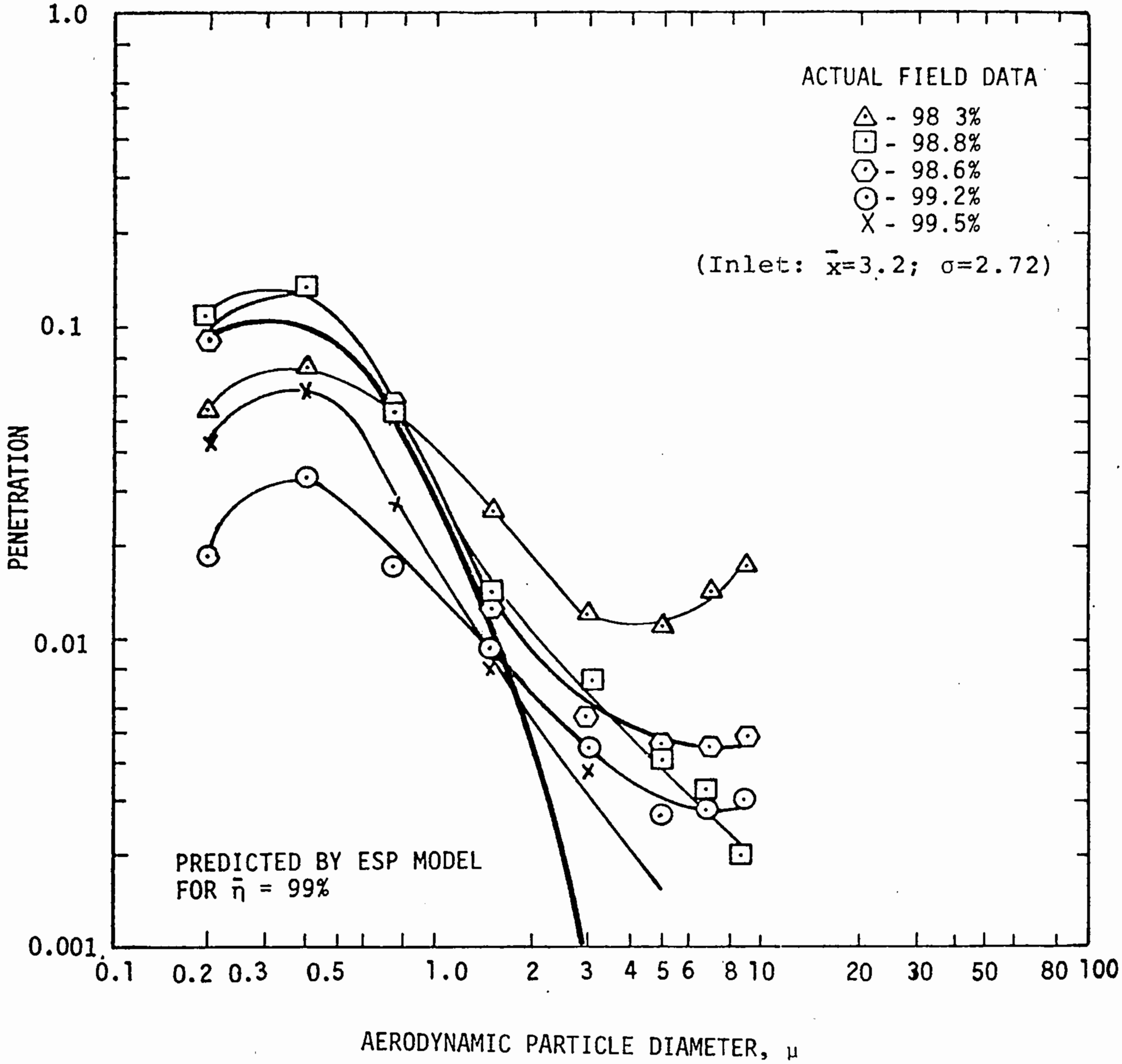


Figure 4.3-8. Computed versus actual penetration for cold-side ESP on a western subbituminous-fired boiler.[2]

sizes, and (3) the fraction of material reentrained remains constant for each mechanical section.

Figure 4.3-9 shows predicted penetration as a function of particle size for four different levels of particle reentrainment, based on the RC model. Note that the maximum penetration is still in the 0.2 to 0.4 μmA size range. Experimental field test data are needed to support the validity of the reentrainment factors.

4.3.3 Design of Electrostatic Precipitators

This section deals with ESP sizing techniques and design considerations for the major ESP components.

4.3.3.1 Sizing Equations and Techniques. The first equation for predicting particle collection probability was developed by Anderson in 1919. It was derived again in 1922 by Deutsch, who used a different method. In various forms, this equation, $\eta = 1 - e^{-(Aw/v)}$, has become the basis for estimating precipitator efficiency on the basis of gas flow, precipitator size, and precipitation rate. In this equation, η is the precipitator collection efficiency, A is the total collecting electrode surface area, V is the gas flow rate, and w is the migration velocity of the particles. When determined empirically, the precipitation rate parameter, w, includes effects of rapping losses, gas flow distribution, and particle size distribution.

The Deutsch-Anderson model assumes that particulate concentration is uniform across any section perpendicular to the gas flow of an ESP. This assumption is made because of the turbulence of the gas, which takes the particles near the collection surface and allows them to become electrically charged. A serious limitation in use of the Deutsch-Anderson equation is that it does not account for changes in the particle size distribution and subsequently in the effective migration velocity, as precipitation proceeds. This limitation affects the accuracy of sizing estimates for units operating at very high efficiencies (approximately 98 percent and above) because of the change in w with particle size.

In practice, factors such as particle reentrainment and gas leakage cannot be accounted for theoretically. Also, some of the most important

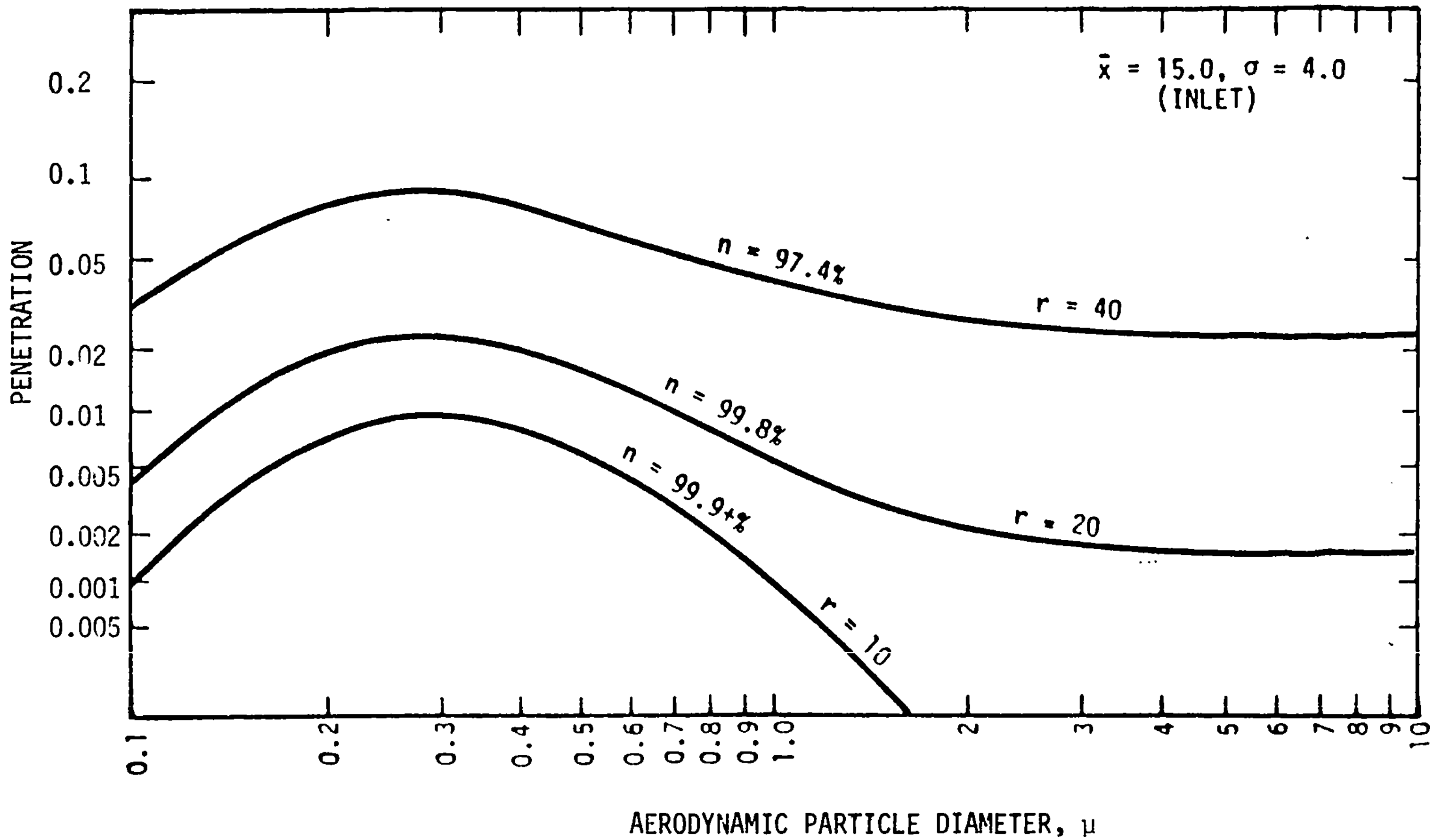


Figure 4.3-9. Predicted precipitator penetration for bark/fossil-fuel-fired boilers ($k = 0.6392 \times 10^{+4}\ m^{-4}$; n = 4 fields; r = percent reentrainment).

physical and chemical properties of the particles and gases often are unknown. Therefore, most designers use an effective precipitation rate parameter, w_e, that is based mainly on field experience rather than theory.[17] Data from operating installations form a general basis for selection of w_e, and these data are modified to fit the situation being evaluated. Thus, w_e becomes a semiempirical parameter that can be used in the Deutsch-Anderson equation or its derivatives to estimate the collection area required for a given efficiency and gas flow.

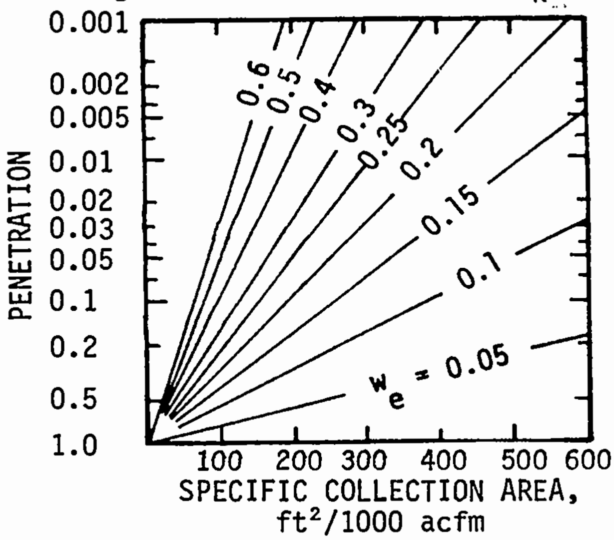
The most important parameters that determine w_e in practice are resistivity, particle size distribution, gas velocity distribution through the ESP, particle loss due to reentrainment, rapping and gas sneakage, ESP electrical conditions, and requied efficiency.[18]

Matts and Ohnfeldt developed a semiempirical modification of the Deutsch-Anderson equation that essentially removes the size dependency from w.[19] This equation is $\eta = 1-e^{-w_k(A/V)k}$. In most cases, k equals approximately 0.5. The modified migration velocity, w_k, can be treated as being independent of charging voltage and current levels and of particle size distribution within an ESP, as precipitation proceeds in the direction of gas flow. Other changes, however, such as in properties of the gas entering the ESP, resistivity, and size distribution, produce a change in w_k, just as they change the conventional w. Other investigators have proposed other forms of the basic penetration equation.[20,21]

Another design technique applied to existing installations or new processes to aid in a full-scale design is the pilot-scale precipitator. The main problem with use of a pilot-scale ESP is that the pilot unit almost always performs better than a full-scale unit because of better gas flow distribution, sectionalization, and electrode alignment.[1,17] The result is operation at higher current densities and voltages than in a full-scale unit. Application of a scale-up factor, as in spark-limited operation of a pilot-scale ESP, can cause uncertainties in sizing the full-scale ESP. Therefore, pilot precipitator data should be supplemented as fully as possible by basic data on particle and gas properties, especially resistivity.[12]

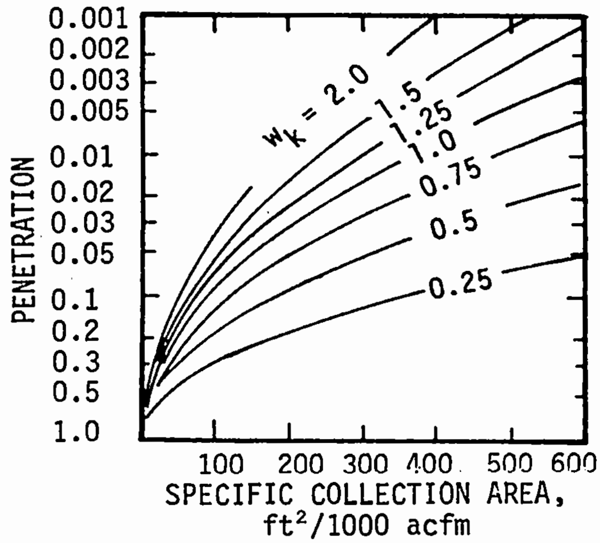
The most important parameters that affect the size of an ESP are collection area, gas velocity, aspect ratio, and structural considerations.

Some variation of the Deutsch-Anderson equation is generally used to estimate the required collection plate area. Figure 4.3-10 presents the relationships of specific collecting areas (SCA's) developed with the Deutsch-Anderson w_e and Matts and Ohnfeldt w_k.



Metric Conversion: ft²/1000 acfm x .055 = m²/1000 m³/sec

Figure 4.3-10a. Precipitator penetration versus specific collection area and precipitation rate w_e.[19]



Metric conversion: ft²/1000 acfm x .055 = m²/1000 m³/sec

Figure 4.3-10b. Precipitator penetration as a function of specific collection area and modified precipitation rate parameter w_k.[19]

The use of sizing equations is only part of the procedure for determining the final collection area. Each manufacturer has a method of computing required plate area, usually involving the use of computer models to assist in the sizing procedure, determination of the amount of redundancy requested by the user or believed necessary by the manufacturer, and some amount of judgment. A recent example of the current approaches of some manufacturers involves the sizing of ESP's for highly variable fuels.[18] Based on ash constituents, fuel sulfur, and the resultant resistivity, and assuming log-normal relationships for log (resistivity) and ash-to-Btu ratio, a contour ellipse is drawn from the bivariate normal distribution (Figure 4.3-11) using the Matts-Ohnfeldt variation of the worst-case fuel. Iso-SCA lines are then plotted on the contour ellipse and the SCA line tangent to the contour ellipse defines the required collection area for the most probable worst case.[18]

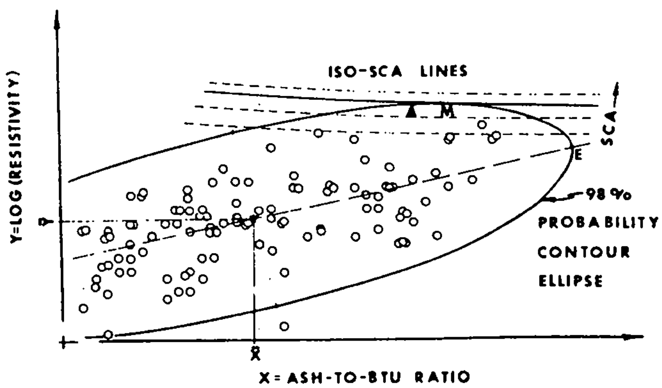


Figure 4.3-11. Distribution of ash-to-Btu ratio and log (resistivity) for a single fuel field. Courtesy of the Air Pollution Control Association

Designers usually calculate a hypothetical average value for gas velocity from gas flow and cross section of the precipitator, ignoring the localized variances within the precipitator. The primary importance of the hypothetical gas velocity is to minimize potential losses through rapping and reentrainment. Above some critical velocity, these losses tend to increase rapidly because of the aerodynamic forces on the particles. This critical velocity is a function of gas flow, plate configuration, precipitator size, and other factors, such as resistivity. Values for gas velocity in fly ash precipitators range from 0.9 to 1.2 m/s in high-resistivity, cold-side ESP applications, and in all low-resistivity applications, hot- or cold-side. For most applications, the values range from 0.9 to 1.7 m/s.

Aspect ratio is defined as the ratio of the length to the height of gas passage. Although space limitations often determine precipitator dimensions, the aspect ratio should be high enough that reentrained dust carried forward from inlet and middle sections can be collected. In practice, aspect ratios range from 0.5 to 1.5. For efficiencies of 99 percent or higher, the aspect ratio should be at least 1.0 to 1.5 to minimize carryover of collected dust.

One of the first structural parameters to be determined is the width of the precipitator(s). This value is dependent on total number of ducts, which is calculated as follows:

$$n = \frac{Q}{Vhs} \qquad \text{(Eq. 4.3-5)}$$

where

n = number of ducts

Q = total gas volumetric throughput, m^3/s

V = gas (treatment) velocity, m/s

h = plate height, m

s = plate spacing, m.

Treatment velocity, V, is a function of resistivity of the fly ash. Values of V should range from 1.0 to 1.2 m/s in high-resistivity, cold-side ESP applications, and in low-resistivity applications, hot-side or cold-side. For most other applications the values should range from 1.0 to 1.5 m/s.

Plate spacing, s, is more or less fixed by the precipitator manufacturer and his experience with different types of fly ash, by velocity distribution across the precipitator, and by plate type. Plate spacing usually ranges from 15 to 40 cm. Most precipitators in the United States have spacing of 22.8 cm, but precipitator designers are now showing a great deal of interest in larger spacings.

Plate height is selected from consideration of simultaneously maintaining the required treatment velocity and also maintaining an adequate aspect ratio. Plate heights usually range from 7.2 to 14.4 m. The practical limitation on plate height imposed by structural stability is obvious. Each manufacturer limits the practical plate heights in accordance with his overall design.

The width of the box is indicated by the total number of ducts. Chamber (parallel) sectionalization is in the direction across the gas flow, whereas series sectionalization is in the direction of gas flow (Figure 4.3-12).

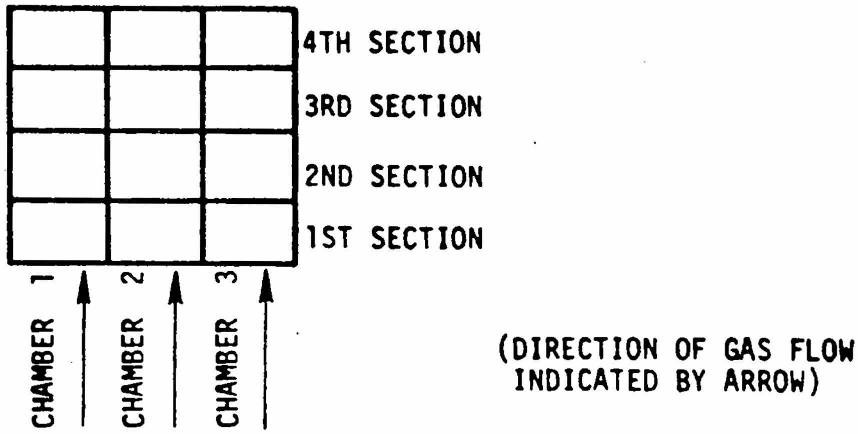


Figure 4.3-12. Mechanical sectionlization of a precipitator.[2]

4.3.3.2 Casings. The casing should be of gas-tight weatherproof construction. Major casing parts are the inlet and outlet transition ducts, shell and hoppers, inspection doors, and insulator housing. The casing should be fabricated of materials suitable for the application. The shell should be reinforced to handle the following: maximum positive or negative pressure static or dead loads of all components, including any equipment located on the roof, superstructure weights, hoppers, or dust loads; loads and movements imposed by connecting flues and dynamic loading caused by vibrators or rappers; and environmental stresses such as those imposed by wind, snow, and earthquake.[22] In addition, design must provide for the overall expansion of the casing caused by the high flue gas temperature. The shell and insulator housing should form a grounded steel chamber completely enclosing all of the voltage equipment to ensure the safety of personnel.

4.3.3.3 Dust Hoppers. Hoppers collect the precipitated dust and deliver it to a common point for discharge. The most common type of hopper is pyramidal, converging to a round or square discharge. If the dust is to be removed by screw conveyor, the hopper usually converges to an elongated opening that runs the length of the conveyor. In applications where the dust is very sticky and may build up on sloping surfaces, hoppers are not recommended; the casing is extended to form a flat-bottomed box under the ESP. The dust is removed by drag conveyors.

Plugging is a major problem with hoppers. Manufacturers have used designs incorporating vibrators, heaters, poke holes, baffles, large discharge flanges, and steep hopper wall angles (55 to 65°) to reduce these problems, but this problem persists at certain installations.

The hopper should usually not be used for storage. The trend is toward larger hoppers so operators can respond to hopper plugging before electrical grounding occurs or before physical damage is done to the electrodes.

Some manufacturers offer a high-ash fail-safe system that automatically deenergizes high-voltage equipment if high-ash levels are detected. Some type of reliable ash level detection is recommended for most hopper designs. If the preliminary design indicates potential problems with discharge of ash, the discharge flange should be no less than 25 cm diameter. Transition from a rectangular hopper to a round outlet should be accomplished without ledges or projections. Heaters have been found to be especially beneficial in the discharge throat and up to one-third the height of the hopper. A low-temperature probe and alarm might also be considered. Hopper installation and enclosing the hopper areas are beneficial in reducing heat loss in the hopper and discharge system.

Hopper aspect ratio (height to width) is an important consideration in minimizing reentrainment caused by gas sneakage to the hoppers. Low aspect ratio hoppers can be corrected by vertical baffling.

4.3.3.4 Power Supplies. A precipitator power supply consists of four basic components: a transformer, a high-voltage rectifier, a control element, and a control system sensor. The system is designed to provide voltage at the highest level possible without causing arc-over (sustained sparking) between the discharge electrode and collection surface.

4.3.3.4.1 Transformer-rectifiers. The unit converts low-voltage alternating current to high-voltage unidirectional current suitable for energizing the precipitator. The transformer-rectifiers and radio-frequency (RF) choke coils are submerged in a tank filled with a dielectric fluid. The RF chokes are designed to prevent high-frequency transient voltage spikes caused by the ESP from damaging the silicon diode rectifiers.[23]

The T-R sets should be matched to ESP load. The ESP will perform best when all T-R sets operate at 70 to 100 percent of rated load without excessive sparking or transient disturbances that reduce maximum, continuous-load voltage and corona power inputs.[23] Over a wide range of gas temperatures and pressures in different applications, practical operating voltages range from 15 to 80 kV at average corona current densities of 100 to 3200 $mA^2/1000$ m^2 (10 to 20 mA/1000 ft^2) of collecting area. Over 1500 mA, T-R set internal impedances are low, which increases the difficulty of achieving stable automatic control. The highest impedance possible that is commensurate with the application and performance requirements should be used. This often means more sectionalization with smaller T-R sets. The high internal impedance of the smaller T-R sets facilitates spark quenching. Smaller electrical sections localize the effects of electrode misalignment and permit higher voltages in the remaining sections.

In general, current ratings should increase from inlet to outlet fields (3 to 5 times for many fly ash precipitators). Typical current voltage characteristics of a five-field fly ash ESP without ash resistivity problems are presented in Figure 4.3-13.[24]

4.3.3.4.2 <u>Subcircuits</u>. During normal operation, optimization of applied power to the precipitator is accomplished by automatic power controls, which vary the input voltage in response to a signal generated by the sparkover rate. Although older ESP's used saturable reactors for power control, modern ESP's use silicon-controlled rectifiers. Provisions are also included to make the circuit current sensitive to overload and to allow control in the event that spark level cannot be reached. Although the circuits may vary among installations, many of the features described below are common.

4.3.3.4.3 <u>Silicon controlled rectifiers (SCR's)</u>. When the circuit breaker and control circuit on/off switch are closed, power flows through the current-limiting reactor, current transformer, and current signal transformer to the primary of the high-voltage transformer. The SCR's act as a

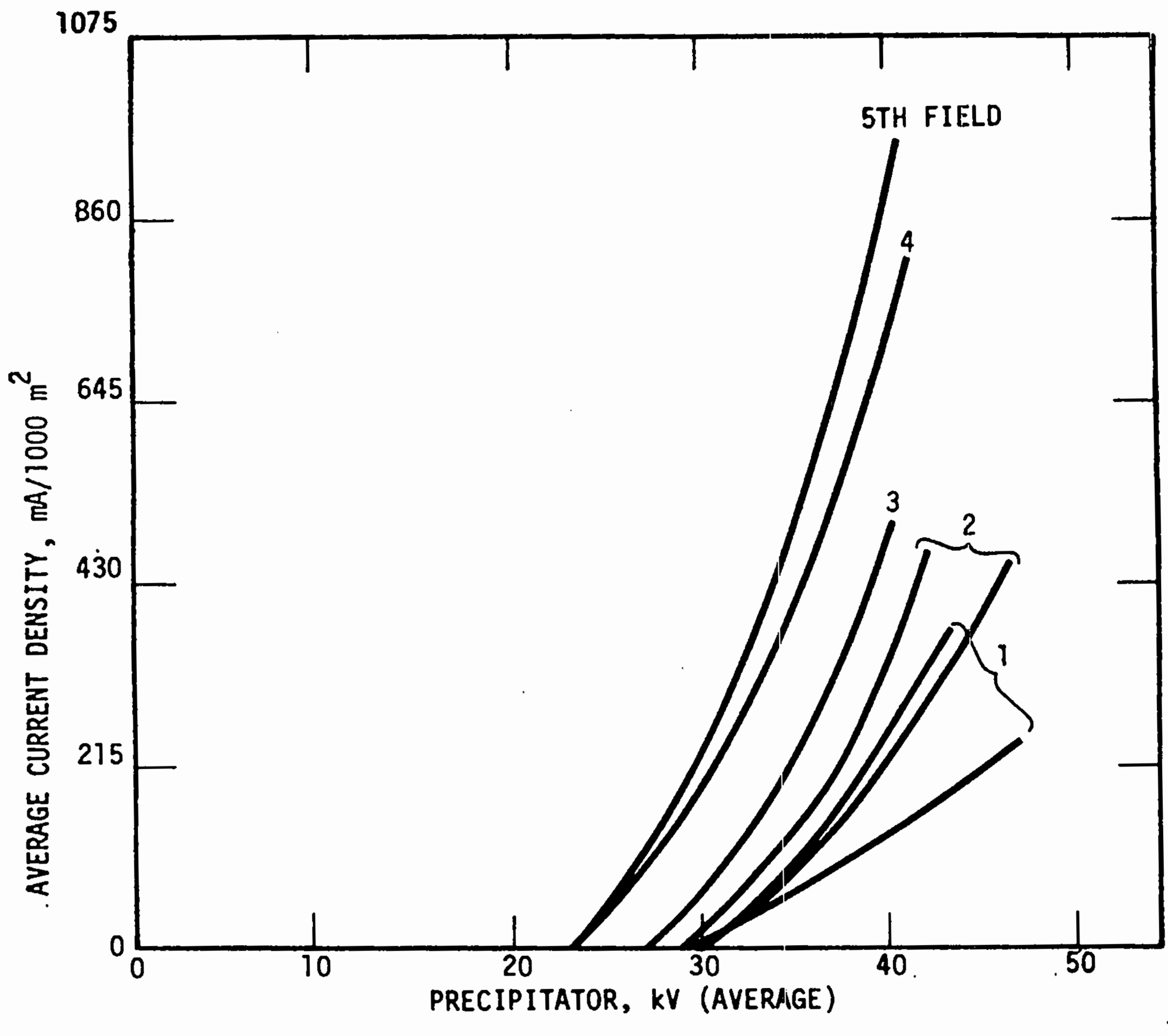


Figure 4.3-13. Typical fly ash precipitator voltage-current characteristics, five fields in series, no ash resistivity problem.[24]

variable impedance and control the flow of power in the circuit. An SCR is a three-junction semiconductor device that is normally an open circuit until an appropriate gate signal is applied to the gate terminal, at which time it rapidly switches to the conducting state. Its operation is equivalent to that of a thyroton. The amount of current that flows is controlled by the forward blocking ability of the SCR's. This blocking ability is controlled by the firing pulse to the gate of the SCR. The current-limiting reactor reshapes the current wave form and limits peak current due to sparking. Current wave form with and without SCR's is illustrated in Figure 4.3-14.

The firing circuit module provides the proper phase-controlled signal to fire the SCR. The timing of the signal is controlled by (1) the potentiometer built in the module, (2) the signal received by the automatic controller, and (3) the signal received by the spark stabilizer.

The automatic control circuit performs three functions: spark control, current-limit control, and voltage-limit control.

4.3.3.4.4 Spark control. Spark control is based on storing electrical pulses in a capacitor for each spark occurring in the precipitator. If the voltage of the capacitor exceeds the preset reference, an error signal will phase the mainline SCR's back to a point where the sparking will stop. Usually this snap-action type of control will tend to overcorrect, resulting in longer downtime than is desirable. At low sparking rates, about 50 sparks per minute, the overcorrection is more pronounced and causes reduced voltage for a longer period, with subsequent loss of dust and low efficiency.

Proportional control, another method of spark control, is also based on storing of electrical pulses for each spark occurring in the precipitator. The phaseback of the mainline SCR's, however, is proportional to the number of sparks in the precipitator. The main advantage of proportional control over spark control is that the precipitator determines its own optimum spark rate, based on four factors: temperature of the gas, ash resistivity, dust concentration, and internal condition of the precipitator. In summary, with proportional spark rate control, the precipitator determines the optimum operating parameters. With conventional spark control, the operator selects the operating parameters, which may not be correct. Figure 4.3-15 shows

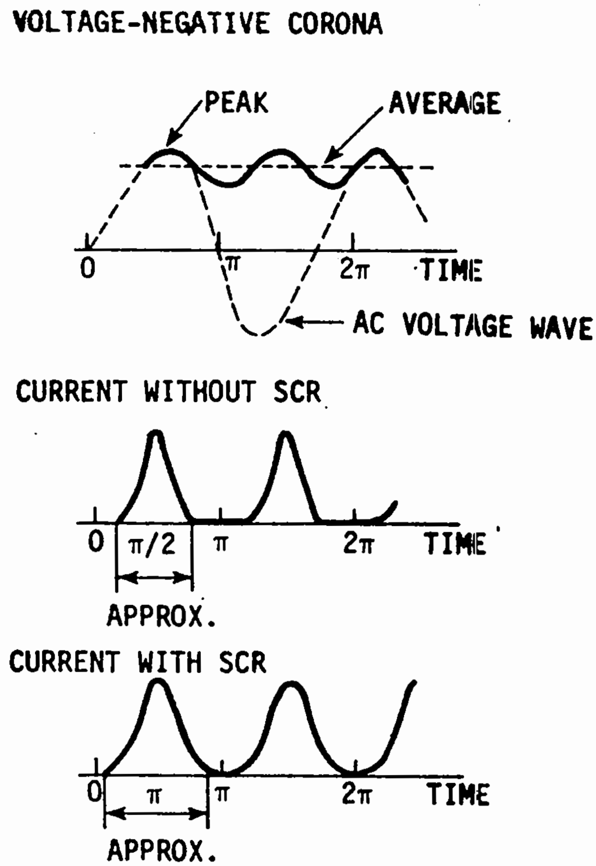


Figure 4.3-14. ESP current wave form with and without silicon controlled rectifiers.[25]

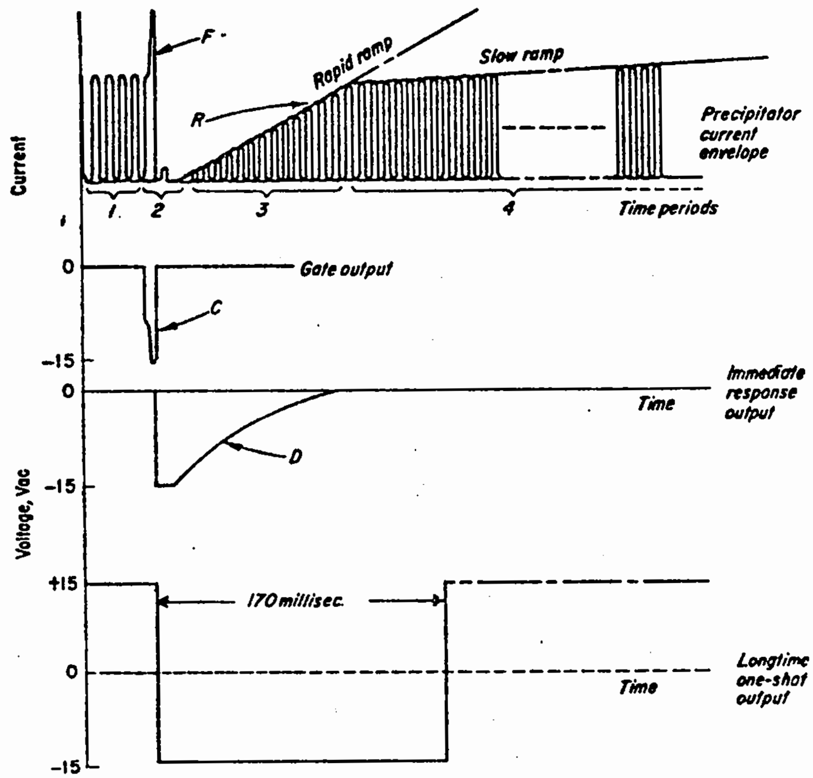


Figure 4.3-15. Time periods are shown as control system reacts to a spark impulse F after steady-state operation. Voltage-start ramp is rapid, then switches to slow until cycle is completed.[25]

voltage current characteristics as an automatic control system reacts to a spark inpulse.

Some precipitators operate at the maximum voltage or current settings on the power supply with no sparking. In collection of low-resistivity dusts, where the electric field and the ash deposit are insufficient to initiate sparking, the no-spark condition may arise. The fact that the precipitator is not sparking does not necessarily indicate that the unit is underpowered. The unit may have sufficient power to provide charging and electric fields without sparking.

4.3.3.4.5 Voltage-limit control. The voltage-limit control feature of the automatic control module limits the primary voltage of the high-voltage transformer to its rating. A transformer across the primary supplies a voltage signal that is compared to the setting of the voltage control, as in the case of the current limit. The voltage control setting is adjusted for the primary voltage rating of the high-voltage transformer. When the primary voltage exceeds this value, a signal is generated that retards the firing pulse of the firing module and brings the primary voltage back to the control setting.

4.3.3.4.6 Current-limit control. For current-limit control, a transformer in the primary circuit of the high-voltage transformer monitors the primary current. The voltage from this transformer is compared with the setting of the current control, which is adjusted to the rating of the transformer-rectifier unit. If the primary current exceeds the unit's rating, a signal is generated, as with spark control, which retards the firing pulse of the firing circuit and this brings the current back to the current-limit setting.

With all three control functions properly adjusted, the control unit will energize the precipitator at its optimum or maximum level at all times. This level will be determined by conditions within the precipitator and will result in any one of the three automatic control functions operating at its maximum, i.e., maximum voltage, maximum primary current, or maximum spark rate. Once one of the three maximum conditions is reached, the automatic control will prevent any increase in power to reach a second maximum. If changes within the precipitator so require, the automatic control will switch from one maximum limit to another.

Other features include secondary overload circuits and an undervoltage trip capability in the event that the voltage on the primary of the high-voltage transformer falls below a predetermined level and remains below that level for a period of time. A time-delay relay is also used to provide a delay period in the annunciator circuit while the network of contacts is changing position for circuit stabilization because of an undervoltage condition.

Panels containing component modules, the SCR power circuit, DC overload circuits, relays, control transformers, resistors, main contactor, current transformer, and other components are mounted in the control cabinet and should be completely accessible for servicing. Positive ventilation for the control unit is provided by an intake fan located near floor level. Ventilating air is exhausted through an opening (grill-protected) in the upper rear of the control unit.

The transformer enclosure is usually a square metal housing bolted to the top of the transformer tank. The enclosure protects the transformer bushings and electrical connections from weather and also ensures, via a key interlock system, that none of the electric connections or bushings can be handled until the associated control cabinet has been deenergized and grounded.

The transformer pipe and guard are used to feed the high-voltage output of the transformer-rectifier to the support bushings, which in turn are connected to the upper high-tension support frame, from which the discharge wires are suspended (Figure 4.3-16).

4.3.3.4.7 Electrical energization/sectionalization. The way in which a precipitator is energized strongly affects its performance. Electrical energization involves the number and size of the transformer-rectifier (T-R) sets, the number of electrical sections, half-wave/full-wave (HW/FW) operation, and changes in the voltage-current characteristics as precipitation proceeds in the direction of gas flow.

Selection of design power density is often conveniently based on resistivity of the dust. Table 4.3-1 illustrates design values of average power density as a function of resistivity for the fly ash applications.

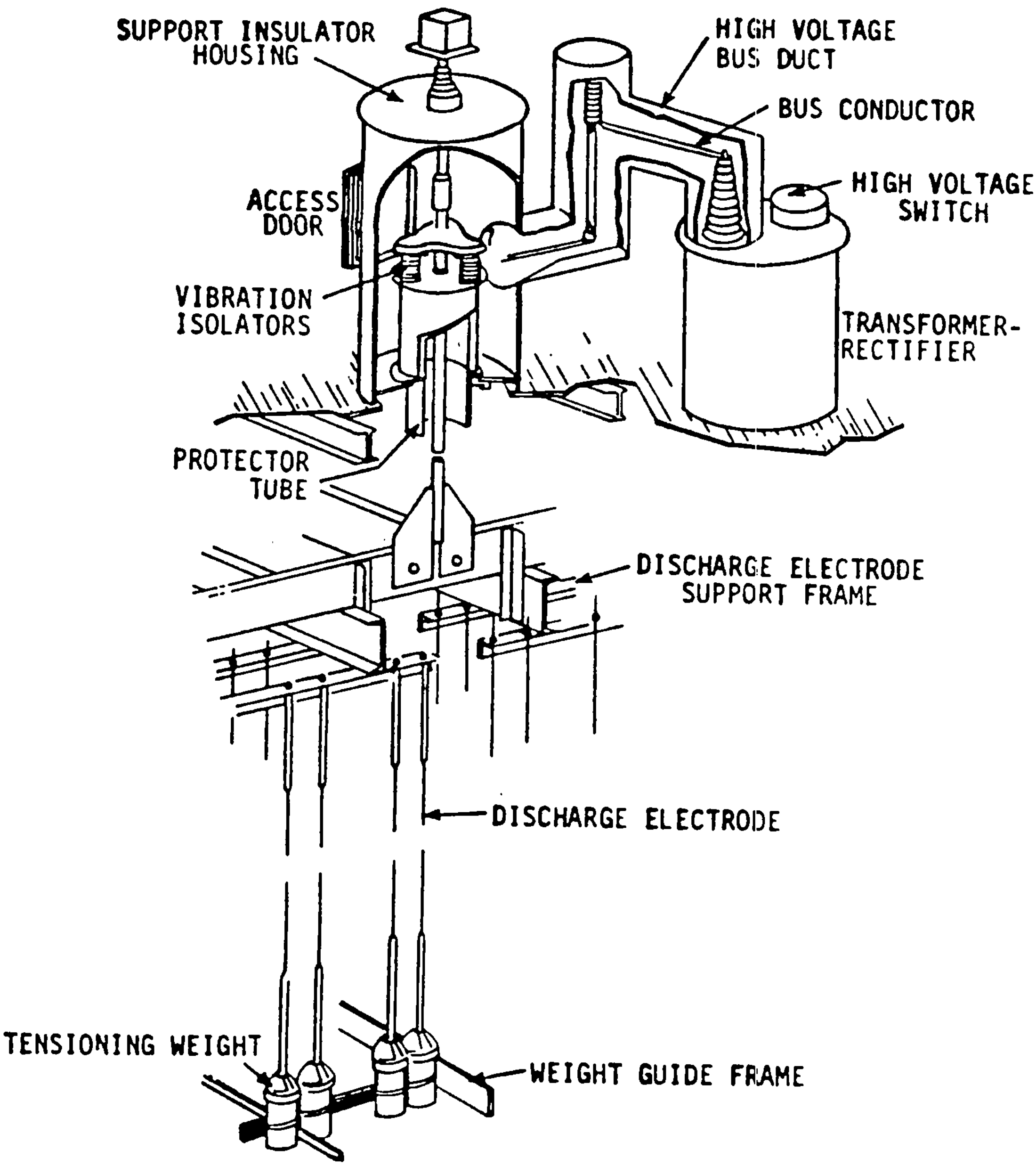


Figure 4.3-16. Precipitator charging system and wire hanging system.[26]

Courtesy of The McIlvaine Co., THE ELECTROSTATIC PRECIPITATOR MANUAL.

TABLE 4.3-1. DESIGN POWER DENSITY[2]

Resistivity, ohm-cm	Power density, w/m^2 of collecting plate
10^{4-7}	40
10^{7-8}	30
10^{9-10}	25
10^{11}	20
10^{12}	15
$>10^{12}$	10

In a cold-side precipitator an average operating voltage may be between 25 and 45 kV for 23 cm spacing, whereas for a hot-side precipitator typical values range from 20 to 35 kV for 23 cm spacing. Knowing power density and operating voltage, one can estimate the current density. The density value of collecting electrode is not constant for each point in the precipitator. At the inlet section, where the dust loading is greatest, the voltage-current characteristics differ significantly from those at the outlet, since the probability of corona suppression is greater at the inlet and the percentage of fine particles is greater at the outlet.

Some powering arrangements are shown in Figure 4.3-17 for a variety of field and cell (chamber) arrangements. The main advantage in splitting a mechanical section by both chamber and section is to provide greater reliability; this is achieved at an increase in cost.

Reliability of the precipitator relates not only to sectionalization of a given collection area but also to the addition of collection area or electrical sections. At the discretion of the designer and in accordance with specifications of the user, the degree of reliability can be defined in terms of a redundant capacity, which is a function of anticipated failure and time between maintenance periods. In this context, redundancy may be defined as that additional area in a precipitator that compensates for the "normal" level of unavailable collecting area. The degree of additional collection area will depend upon the application and the manufacturer's

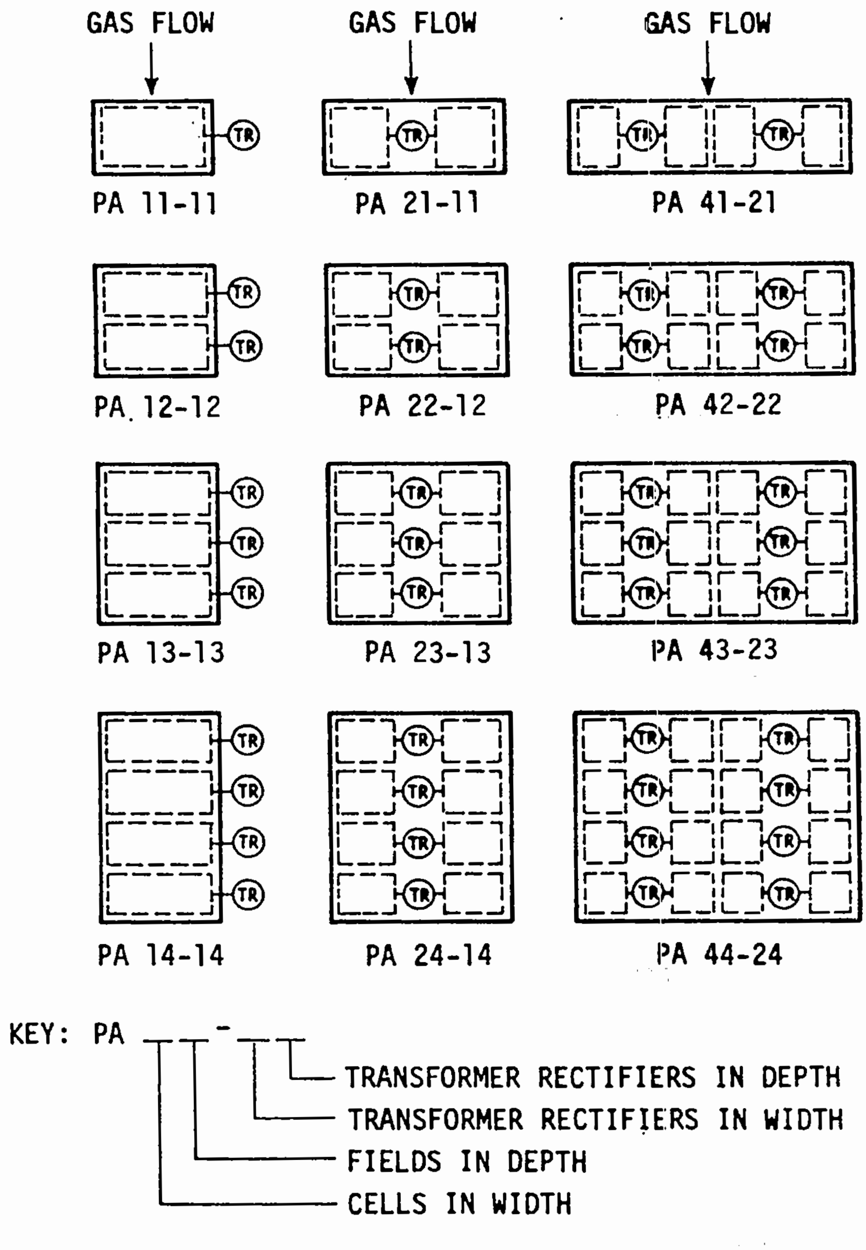


Figure 4.3-17. Various combinations of electrical sectionalization in an ESP.[27]

Courtesy of The McIlvaine Co., THE ELECTROSTATIC PRECIPITATOR MANUAL.

experience. To provide a reliable yet cost-competitive design, the designer must have detailed information on the composition of the particulate and the physical and chemical parameters of the gas stream.

The highest efficiency of a precipitator is achieved when useful power input is maximized. The number, size, and mode of operation (half-wave or full-wave) of the T-R sets can be manipulated to provide the required current density within each electrical section of the precipitator. Full-wave energization involves the powering of two bus sections from a common power supply, whereas with double-half wave, the two sections are energized separately. The selection of half-wave or full-wave operation will depend on the source-specific parameters in the optimization of ESP power input.

In spark-limited operation on a cold-side precipitator treating high-resistivity ash, half-wave operation allows time during the off half cycle to recover from the sparking condition (spark quenching). Complete decay of the charging field and of collection efficiency during the off half cycle is avoided because of the capacitive effect of high-resistivity fly ash, which tends to maintain the field potential.

In operation of hot-side precipitators, fly ash resistivity is reduced by the increase in operation temperature, and the capacitance effect of the fly ash is reduced. Thus, the charging field decays faster in half-wave than in full-wave operation.

In summary, the design considerations in sectionalization and energization are based on maximizing the power input to the precipitator to achieve the highest efficiency from a given collection area while minimizing loss of performance as a result of various potential failures. Reliability of precipitator performance is a function of application and design experience. Precipitator energization depends on the sectionalization configuration and the current density to be supplied to each electrical section, as determined by chemical and physical characteristics of the dust, dust loading, and characteristics of the gas stream. The number, size, and mode of operation of the T-R sets can be fitted to the sectionalized configuration after the bus section design has been established.

4.3.3.5 <u>Electrode Characteristics</u>.

4.3.3.5.1 <u>Discharge electrodes</u>. Discharge electrodes may be cylindrical or square wire, barbed wire, or stamped of formed strips of metal of various configurations. The geometry of the electrode determines the current-voltage characteristics; e.g., the smaller the wire or the more pointed its surface, the greater the observed value of current for a given voltage.

Discharge electrodes may be suspended from an insulating superstructure with weights at the bottom holding them tightly in place, or they may be rigidly mounted on mats or frames. The weighted-wire type must be stabilized against swinging in the gas stream. An example of rigid wire systems is shown in Figure 4.3-18. The rigid type of discharge electrode system requires a high degree of quality control during fabrication and erection, making it more costly than the weighted-wire system. Replacement or repair is expensive and time consuming. Larger casings are generally required because of the greater spacing between plates. Two potential problems with discharge electrodes are summarized below.

4.3.3.5.2 Electrical erosion. In situations where high-current sparks or continuous sparking must be tolerated, the larger discharge electrodes will provide more protection against erosion than will smaller sizes. Shrouds should be included at both the top and bottom of weighted-wire electrodes, and all interelectrode high-voltage and grounded surfaces should have smooth surfaces to minimize spark-over. Transformer-rectifier sets should be matched to precipitator load, and automatic spark controllers should keep voltage close to the sparking theshold. Contact between the electrode and the stabilizing frame should be solid to prevent sparking. With rigid discharge electrodes, substantial reinforcement should be provided at the point where the electrode is attached to the supportframe, so that a significant amount of metal must be lost before failure occurs. The rigid type discharge electrode system has an advantage in that if a wire does break, there is less chance of it falling against a plate and shorting out a section of the ESP.

4.3.3.5.3 Mechanical fatigue. Mechanical connections in the discharge electrode structure should be designed to minimize flexing and reduction in cross-sectional area at junction points. Connections should be resistant to vibration and stress, and electrodes should be allowed to rotate slightly at their mounting points. Reducing the number of welds is also desirable. Keeping the total unbraced length of electrode as short as possible will

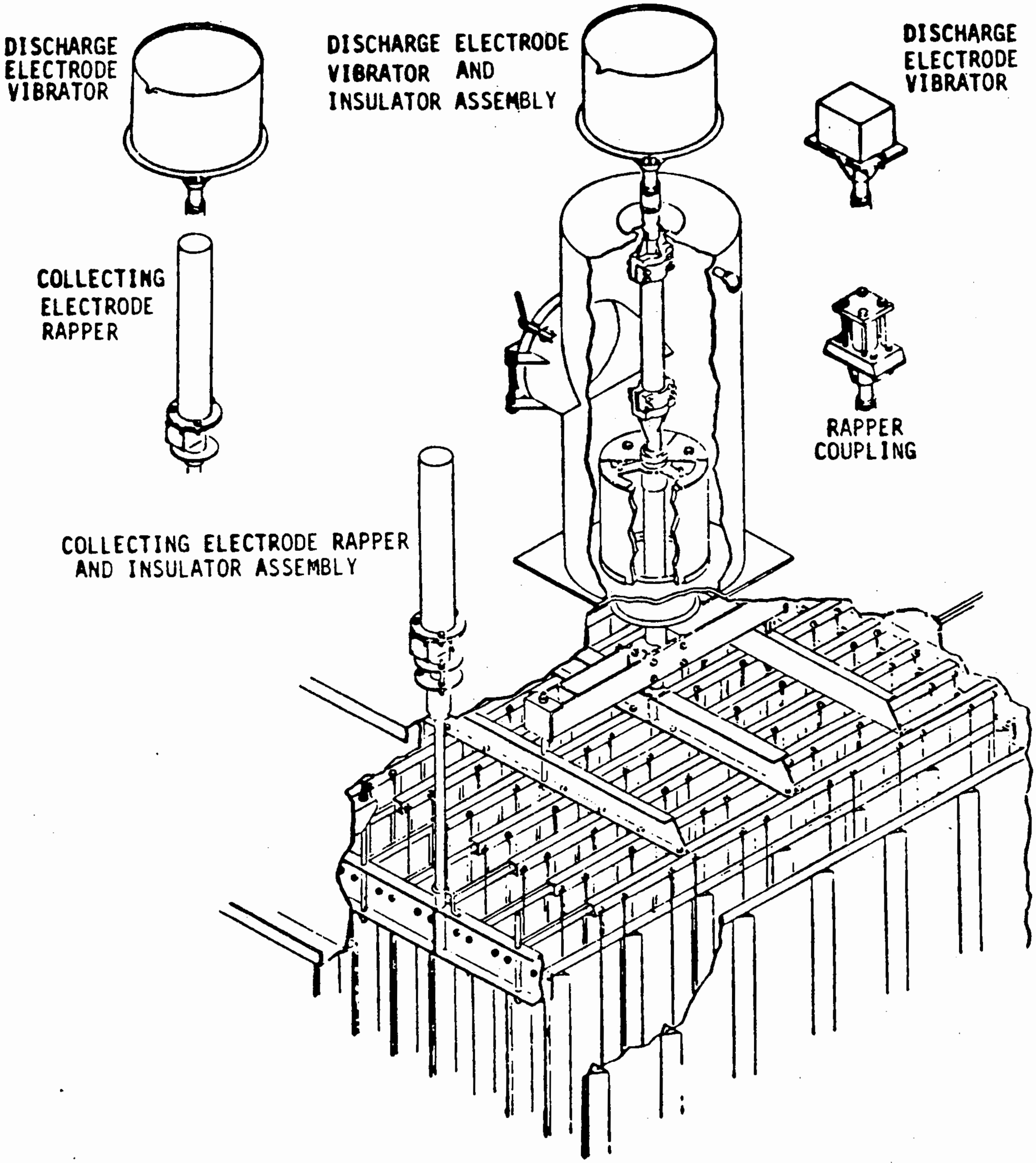


Figure 4.3-18. Vibrator and rapper assembly and precipitator high-voltage frame.[2]

help minimize mechanical fatigue. Adequate tension during the construction process is vitally important for weighted-wire electrodes, and hard spring wire should be used to prevent kinking.

Schneider et al.[22] emphasized that electrode wire failure can be kept to a minimum provided:

1) Reasonable care is taken during erection in alignment of casings and surfaces.
2) The support, guide, and stabilizer system is well designed.
3) Reliable, properly adjusted voltage supplies are provided.
4) There is good operating maintenance of the dust handling system.

4.3.3.5.4 Collection electrodes. Collection plates are commercially available in lengths ranging from 1 to 3 meters and heights from 3 to 15 meters. Generally, these panels are grouped with the precipitator to form independently rapped collection modules. The total effective length of these plates divided by their effective height is referred to as the aspect ratio. Aspect ratios larger than 1.0 provide longer residence time for the gas and reduce penetration, all other things being equal. Although a variety of plates are commercially available, their functional characteristics are not substantially different. Collection plates should be straight and parallel with the discharge electrodes when assembled. This alignment depends on care during fabrication, shipping, storage in the field, and erection.

The ruggedness of the plate support system is also important since in many designs it must also transmit rapper energy to the plates. Each design should be examined for its operating limits with various types of rappers. The effects of vibration and impact loading at all welded points should be considered. There should also be consideration for adjustment of plate alignment if necessary after shakedown. Enough spacers should be provided to maintain alignment and allow for temperature variations.[22]

Rapper anvils attached to either dust plate supports or rapper header beams should be durable enough to withstand the stress of rapping and maintain alignment (no bending of flanges or other local deformations).

4.3.3.6 Rapper Characteristics.

4.3.3.6.1 Rapper types. For the weighted-wire design rapping impulses are provided by either single impulse or vibratory type rappers, which are activated either electrically or pneumatically.

The electromagnetic or pneumatic impulse type rappers are usually better for collection electrodes and difficult applications, as a vibrator usually cannot generate sufficient operating energies without being damaged.[28] The magnetic-impulse, gravity-impact rapper is a solenoid electromagnet consisting of a steel plunger surrounded by a concentric coil, both enclosed in a watertight steel case. The control unit contains all the components (except the rapper) needed to distribute and control the power to the rappers for optimum precipitation.

During normal operation, a dc pulse through the rapper coil supplies the energy to move the steel plunger. The plunger is raised by the magnetic field of the coil and then is allowed to fall back and strike a rapper bar, which is connected to the collecting electrodes within the precipitator. The shock transmitted to the electrodes dislodges the accumulated dust.

The electrical controls provide separate adjustments so that rappers can be assembled into different groups and each group adjusted independently to achieve optimum rapping frequency and intensity. The controls are adjusted manually to provide adequate release of dust from collecting plates while preventing undesirable stack puffing.

In some applications, the magnetic-impulse, gravity-impact rapper is also used to clean the precipitator discharge wires. In this case the rapper energy is imparted to the electrode supporting frame in the same manner, except that an insulator isolates the rapper from the high voltage of the electrode supporting frame.

The vibrator is also an electromagnetic device--a coil that is energized by alternating current. Each time the coil is energized, the vibration is transmitted to the high-tension wire supporting frame and/or collecting plates through a rod. The number of vibrators applied depends on the number of high-tension frames and/or collecting plates in the system.

The control unit contains all components necessary for operation of the vibrators, including adjustments for vibration intensity and the length of the vibration period. Alternating current is supplied to the discharge wire vibrators through a multiple cam-type timer to provide the sequencing and time cycle for energization of the vibrators.

The number of rappers, size of rappers, and rapping frequencies vary with the manufacturer and the nature of the dust. Generally, one rapper unit is required for 110 to 150 m^2 of collecting area. Discharge electrode rappers serve from 350 to 2000 m of wire per rapper. Intensity of rapping generally ranges from about 35 to 70 J, and rapping intervals are adjustable over a range of approximately 50 to 600 s.

For each installation, a certain intensity and time period of vibration produces the best collecting efficiency. Insufficient intensity in the discharge vibrators may cause heavy buildup of dust on the discharge wires, which can lead to the following adverse operating conditions:

It reduces the spark-over distance between the electrodes, thereby limiting the power input to the precipitator.

It tends to suppress the formation of negative corona and the production of unipolar ions required for the precipitator process.

It alters the normal distribution of electrostatic forces in the treatment zone. Unbalanced electrostatic fields can cause the discharge wires and the high-tension frame to oscillate.

Rigid frame designs generally utilize mechanical hammer rappers. In these installations, each frame is rapped by one hammer assembly mounted on a shaft. A low-speed gear motor is linked to the hammer shaft by a drive insulator, fork, and linkage assembly. Rapping intensity is governed by the hammer weight, and rapping frequency is governed by the speed of the shaft rotation.

4.3.3.7 Solids Removal Equipment. Solids removal from ESP's may be performed by pressure or vacuum system in large systems such as utility applications, and by screw conveyor in many smaller industrial applications. Dust can also be wet sluiced directly from the hoppers. Once conveyed from the hoppers, the dust can be disposed of dry, or wet sluiced to a holding pond.

4.3.3.7.1 Removal from the hopper. An air seal is required at each hopper discharge. Air locks provide a positive seal, although tipping or air operated slide gate check valves are also used. Heaters, vibrators, and/or diffusers are frequently considered because bridging in the hoppers occurs at least occasionally. In trough-type hoppers, a paddle-type conveyor has been shown to be the best means of transporting the dust to the air lock. Dust valves are often oversized to help facilitate removal of dust from the hopper.

4.3.3.7.2 Pneumatic systems. Figure 4.3-19 shows a typical fly ash type pneumatic vacuum system. The length of a vacuum system is limited by the configuration of the discharge system and the altitude above sea level. Pressure systems are applied when the limits for vacuum systems are exceeded. When the number of hoppers exceeds about 20 and the length of the system is too great for a vacuum system, combination vacuum pressure systems may be used.

A vacuum is produced hydraulically or with mechanical vacuum pumps. Positive displacement blowers are used with pressure systems. Vacuum systems use electric valves and slide gates, whereas pressure systems use air locks and slide gates.

Materials of construction are extemely important in selection of a solids removal system. The chemical composition of the dust and of the conveying air, and temperatures at various points in the conveying system should be determined.

When material characteristics are known (material density, particle size, concentration, and the physical characteristics of the conveying air or gas) the required conveying velocity can be determined. The design rate is usually set at 20 percent above the theoretical maximum conveying capacity to avoid plugging.[29]

Storage facilities for pneumatic dust handling generally are equipped with cyclones, and often with a fabric filter. The dust is then conditioned with water and/or a wetting agent and transported by truck or rail to a disposal site or is mixed with water and pumped to a disposal pond.

4.3.3.8 Gas Distribution Equipment. Proper gas flow distribution is critical for optimum precipitator performance. Areas of high velocity can cause erosion and reentrainment of dust from collecting surfaces or can allow gas to move virtually untreated through the precipitator. Improper gas flow distribution in ducts leading to the precipitator result in dust accumulation on surfaces and high pressure losses.

Devices such as turning vanes, diffusers, baffles, and perforated plates are used to maintain and improve gas flow distribution. A diffuser

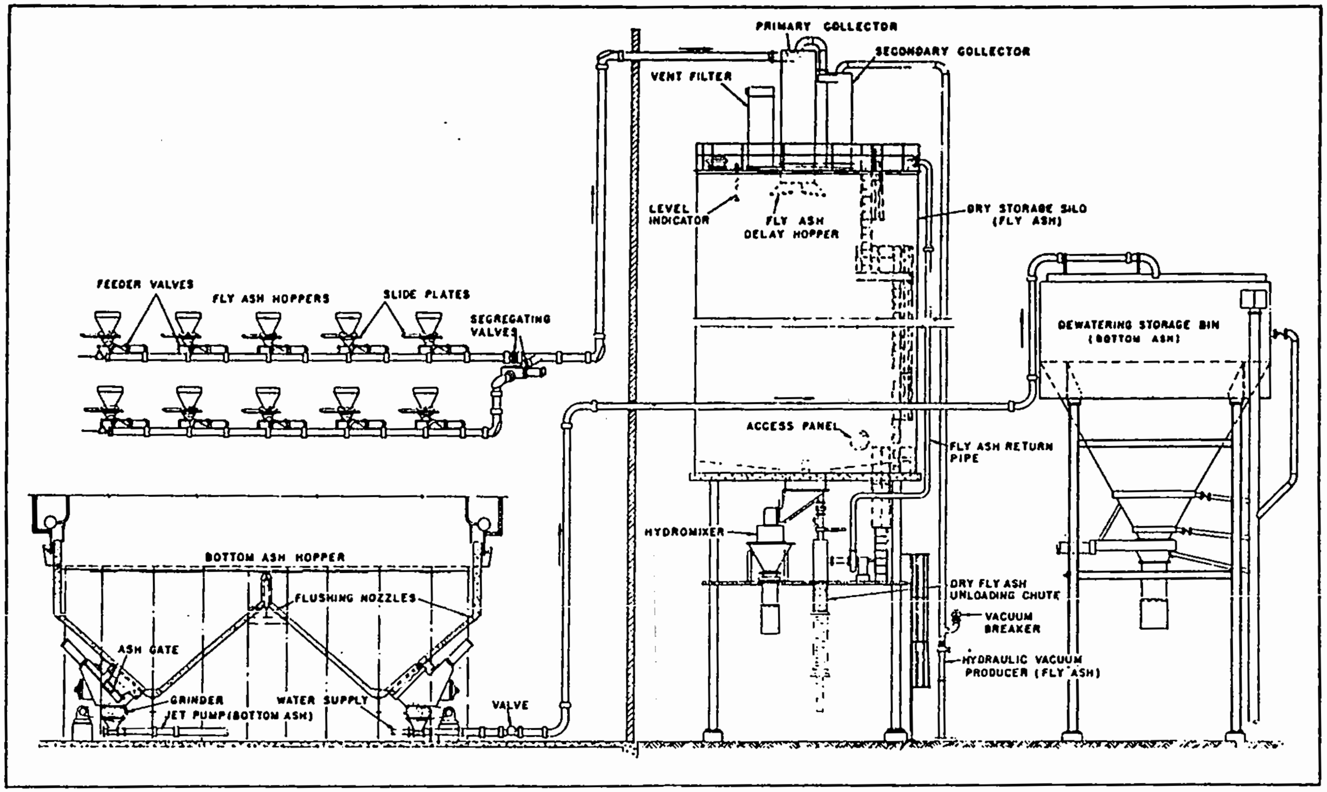


Figure 4.3-19. Typical fly ash type pneumatic vacuum system.[29]

Courtesy of Allen-Sherman-Hoff Company.

consists of a woven screen or a thin plate with a regular pattern of small openings. The effect of a diffuser is to break large-scale turbulence into many small-scale turbulent zones, which in turn decay rapidly and in a short distance coalesce into a relatively low-intensity turbulent flow field.[30] Two or three diffusers may be used in series to provide better flow than could be achieved with only one diffusion plate.[30] Gas distribution devices may require rapping for cleaning.

Katz[31] stresses the need for uniformity in designing inlet and outlet nozzles of ESP plenums and their distribution devices. Examples of good and bad flue and distribution device design for inlet and outlet flues are shown in Figures 4.3-20 through 4.3-22, respectively.

In multiple-chamber ESPs, louver-type dampers are commonly used for gas proportioning. At the inlet, however, guillotine shutoff dampers should not be used for proportioning because they tend to destroy proper gas distribution to a chamber.[22]

Gas sneakage through hoppers can be caused by poor gas distribution. Expansion-type plenums or top entry plenums cause gas vectors to be directed towards the hopper, and if multiple perforated plates do not fit well in the lower portion of the plenum or if the lower portion has been cut away because of dust buildup, gas is channeled into the hoppers.[31] Short-circuiting the ESP and/or reentrainment is the end result.

4.3.3.8.1 Gas flow models. Gas flow models are used to determine the location and configuration of gas flow control devices. Although flow model studies are not always effective in developing the desired distribution, they are at least a qualitative indicator of the distribution.

Temperature and dust loading distributions are also important to efficient ESP operations. It is generally assumed that the temperature of the flue gas is uniform. This is not always true, however, and the effects of gas temperature on ESP electrical characteristics should be considered.[32]

Dust loading distributions are not modeled at present for ESP's. It is assumed that the dust is evenly distributed in the gas, and that as long as the gas distribution is of a predefined quality, no dust deposition problems will occur. However, problems such as poor flue design, poor flow patterns at the inlet nozzle of the ESP plenum, and flow and wall obstructions can cause dust deposition that gas flow models cannot anticipate.[31]

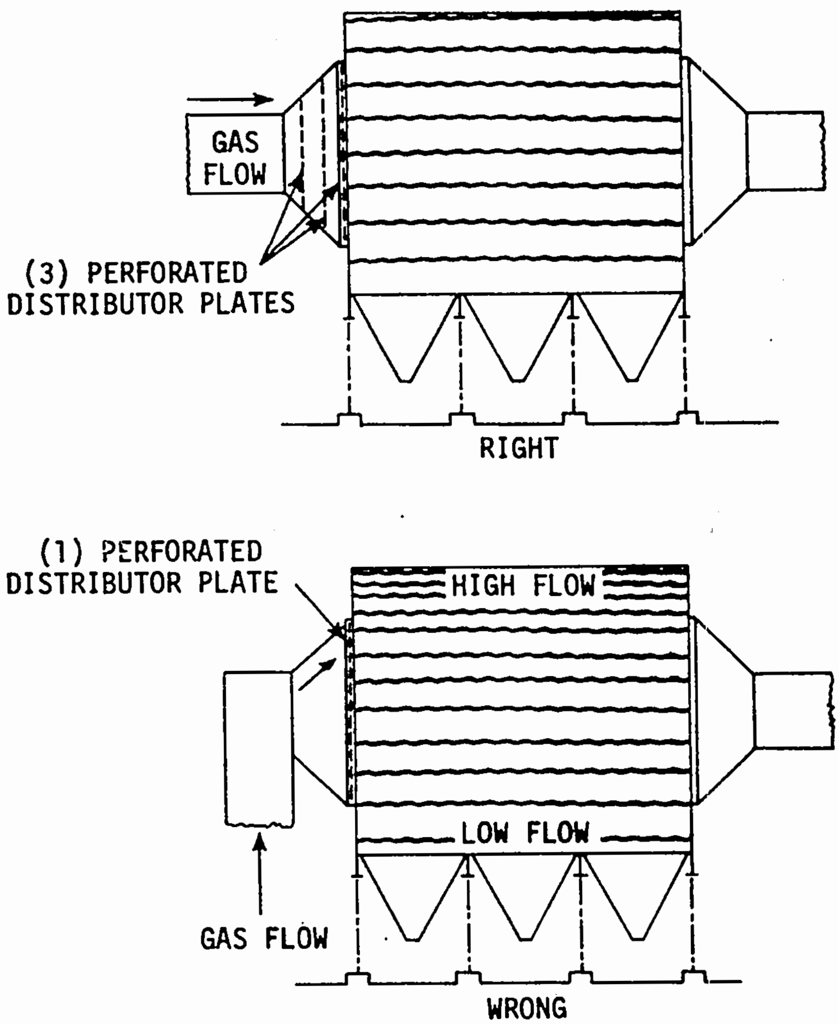


Figure 4.3-20. Effect of two different methods of gas distribution on flue characteristics in an ESP.[30]

Courtesy of McGraw-Hill.

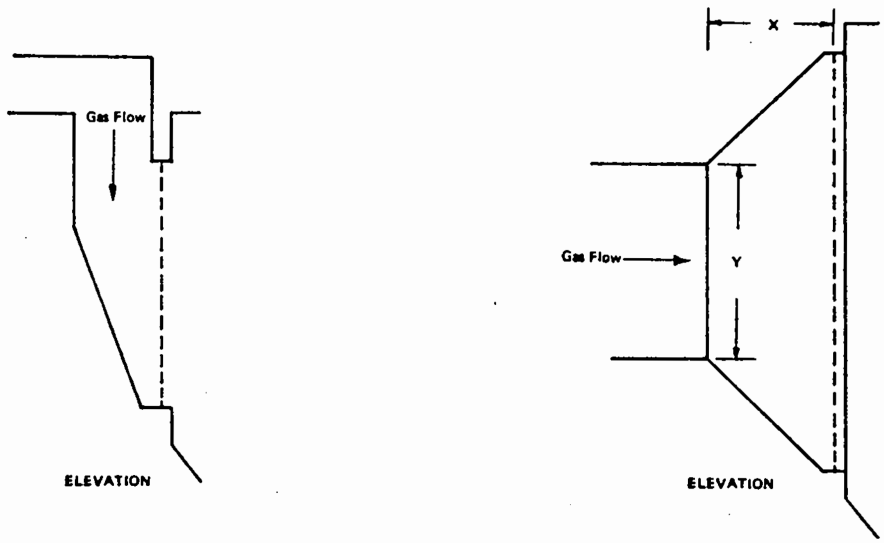


Figure 4.3-21. Examples of two inlet plenum designs that generally cause gas distribution problems.[31]

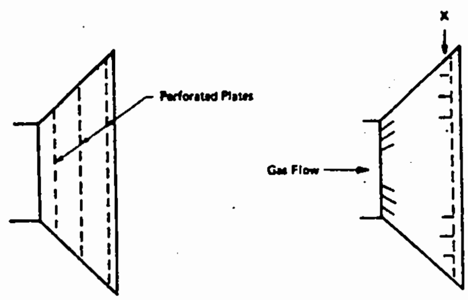


Figure 4.3-22. Expansion inlet plenums showing two methods of spreading the gas pattern.[31]

Courtesy of Precipitator Technology, Inc.

4.3.3.9 Instrumentation. Instrumentation necessary for proper monitoring of ESP operation can be categorized by location; i.e., T-R sets, rappers/vibrators, hoppers/dust removal systems, and external items.

4.3.3.9.1 T-R sets. Power input is the most important measure of the ESP performance. Thus any new ESP should be equipped with the following:

Primary current meters
Primary voltage meters
Secondary current meters
Secondary voltage meters
Spark rate meter (optional)

These meters are considered essential for performance evaluation and troubleshooting. Figure 4.3-23 shows a typical control cabinet and T-R set instrumentation.

Data loggers (mainly for digital automatic control systems) are available to help speed troubleshooting and reduce operating labor. Oscilloscopes are also useful in evaluating power supply performance and identifying the type of sparking (multiple burst versus single arc) but there is little demand for such devices.

It is also possible to use feedback signals from transmissometer, full hopper detectors, gas conditioning systems, rappers, and suitable process fault indicators in conjunction with the automatic control unit to provide optimum performance under all conditions.[23] An example is automatic phase-back of T-R sets when hoppers are overfilled, preventing the burning of discharge wires.

4.3.3.9.2 Rappers/vibrators. Microprocessor type technology is available for a high degree of rapper control flexibility and ease of maintenance. For example, in order to prevent control damage from ground faults, new controls will test each circuit before energizing it. If a ground fault occurs, the control will automatically bypass the grounded circuit and indicate the problem on an LED display, thus permitting fast location and solution of the problem.[33]

Instrumentation should be used in conjunction with a transmissometer to help in troubleshooting ESP problems. Separate rapping instrumentation should be provided for each field. Readings of frequency, intensity, and

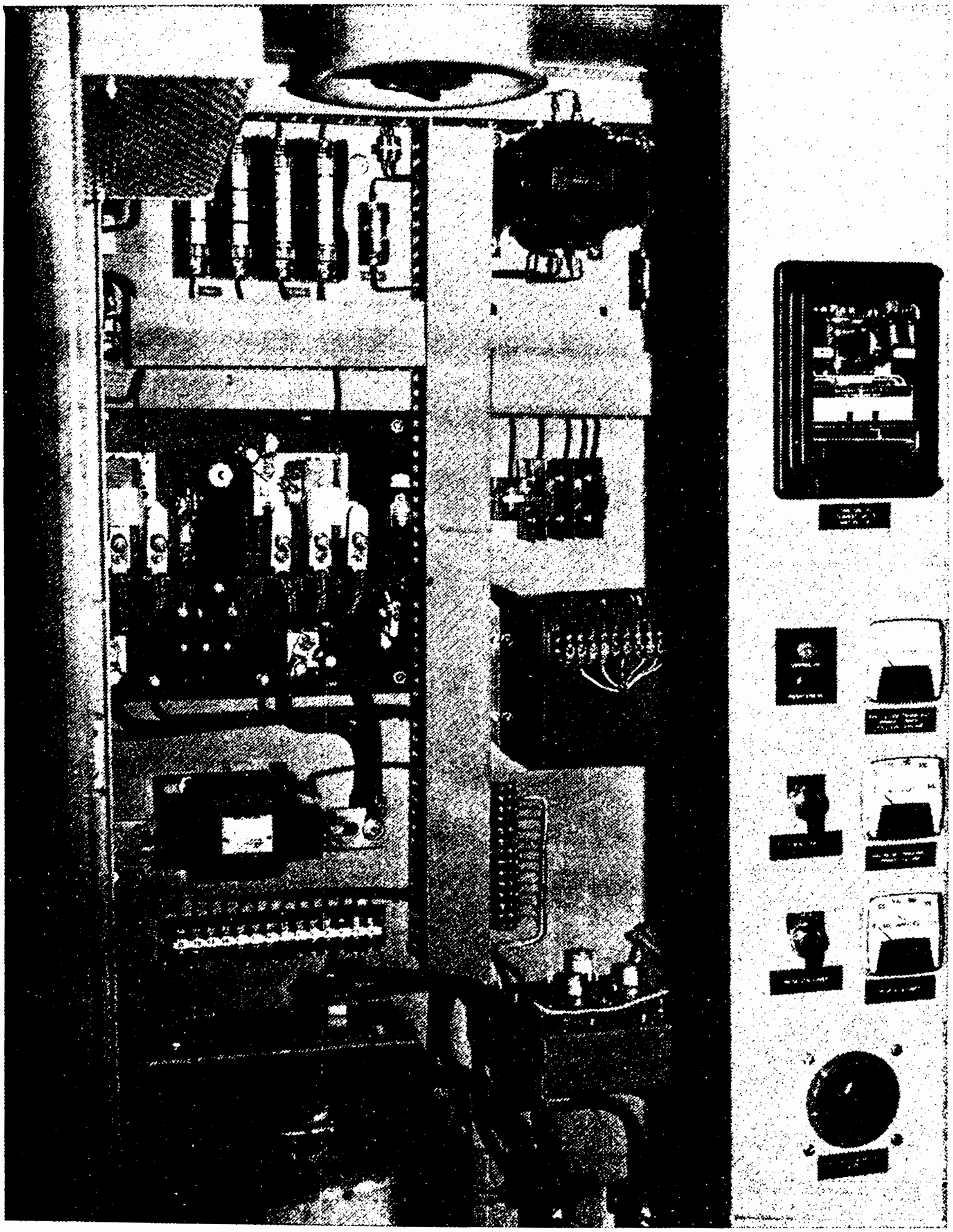


Figure 4.3-23. Internal view of one type of rectifier console showing component parts.

Courtesy of Koppers Co., Inc.

cycle time can be used with T-R set controls to properly set rapper frequency and intensity, in the case of the weighted-wire electrodes.

For rigid frame mechanical rappers, cycle time and rap frequency of both internal and external types are easy to measure. Individual operation of internal rappers is not easily instrumented, nor is intensity control possible without a shutdown of the ESP.[34]

4.3.3.9.3 Hoppers. Instrumentation should be provided for detecting full hoppers and for operation of the dust valve and dust removal system.

Level detectors can utilize gamma radiation, sound capacitance, pressure differential, or temperature.[31] The alarms should be located so that filling of hoppers does not occur but frequent alarms are avoided. A low-temperature probe and alarm can be used in conjunction with the level detector. Control panel lights are used to indicate the operation of hopper heaters and vibrators.[34]

Zero motion switches are used on rotary air lock valves to detect malfunction, as well as on screw conveyors. Pressure switches and alarms are normally used with pneumatic dust handling systems to detect operating problems.

4.3.3.9.4 Fans. Fans should be equipped with static pressure gages, ammeters, and vibration indicators to assist in detecting abnormal operating conditions.[34]

4.3.3.10 Gas and Particle Conditioning. In the United States, gas and particle conditioning agents are used primarily to improve ESP collection efficiency when they are operated on low-sulfur coal having high-resistivity fly ash. Some older ESP's designed for higher-sulfur coal usually cannot operate efficiently enough to meet emission regulations on low-sulfur coal without flue gas conditioning. Other alternatives are increasing the size of the ESP, cooling the gas below the design temperature of the ESP, or switching to a hot-side ESP. Some hot-side ESP's appear to require chemical conditioning in order to perform as designed.

4.3.3.10.1 Conditioning agents and mechanisms. The compounds other than water that are now used or under study as conditioning agents are sulfur trioxide, sulfuric acid, ammonia, ammonium sulfate, triethylamine, compounds of sodium, and compounds of transition metals. Table 4.3-2 summarizes these conditioning agents and their mechanisms of operation.

TABLE 4.3-2. REACTION MECHANISMS OF MAJOR CONDITIONING AGENTS

Conditioning agent	Mechanism(s) of action
Sulfur trioxide and sulfuric acid	Condensation or adsorption on fly ash surfaces; may also increase cohesiveness of fly ash. Reduce resistivity.
Ammonia	Mechanism is not clear; various ones proposed: Resistivity modification Increase in ash cohesiveness Enhances space charge effect.
Ammonium sulfate	Little known about the actual mechanism; claims made for the following: Resistivity modification Increase in ash cohesiveness Enhances space charge effect. Experimental data lacking to substantiate which of the above is predominant.
Triethylamine	Particle agglomeration claimed; no supporting data.
Sodium compounds	Natural conditioner if added with coal Resistivity modifier injected into gas stream.
Compounds of transition metals	Postulated that they catalyze oxidation of SO_2 to SO_3; no definitive tests with fly ash verify this postulation.
Potassium sulfate and sodium chloride	In cement and lime kiln ESP's: Resistivity modifiers in the gas stream NaCl: natural conditioner when mixed with coal.

Sulfur trioxide and sulfuric acid are the most widely used conditioning agents in the United States. The primary mechanism is condensation or adsorption on ash. Handling of both of these compounds is difficult because they are highly corrosive and toxic liquids that must be vaporized before injection to the flue gas. A typical SO_3 conditioning system is illustrated in Figure 4.3-24.

Ammonia is less widely used in the U.S. mainly because of its inconsistent rate and lack of a clear indication of the mechanism by which it acts.[35] In some cases, ammonia shows a significant resistivity reduction, while in other cases it does not.

Ammonium sulfate is believed to be a main component of many commercial formulations presently used.[35] It is thermally decomposed to ammonia, sulfur trioxide, and water after being injected into the flue gas at high temperature about 600°C (355°F) and reforms ammonium sulfate as the temperature decreases. Although a number of mechanisms have been claimed to be responsible for the action of ammonium sulfate, experimental test data are not available to document which mechanism is predominant.[35]

Triethylamine is not being used in the U.S. but other proprietary formulas used here claim to have the same operating mechanisms, namely, agglomeration. There is doubt as to whether agglomeration actually occurs since no tests that measure a change in particle size distribution with triethylamine have been conducted.

Sodium compounds have been used for both cold- and hot-side ESP's, and interest in these compounds stems from their role as a natural substance in reducing resistivity in coal ash. Sodium can be added either with the coal fed into the boiler or by conventional means as a solid powder or aqueous solution in the gas stream. The latter would probably result in a reduction in the resistivity since it is co-precipitated with the ash rather than being chemically incorporated into it. Full-scale tests of sodium (soda ash) both in the lab and in the field have shown it is the conditioning agent of choice for hot-side ESP's.[36] A solution type injection appeared to offer the most effective utilization of the chemical.

Tests with anhydrous sodium carbonate injected into the flue gas preceding a cold-side pilot ESP treating ash from a boiler firing low-sulfur coal showed a sixfold reduction in ash resistivity, an improvement in

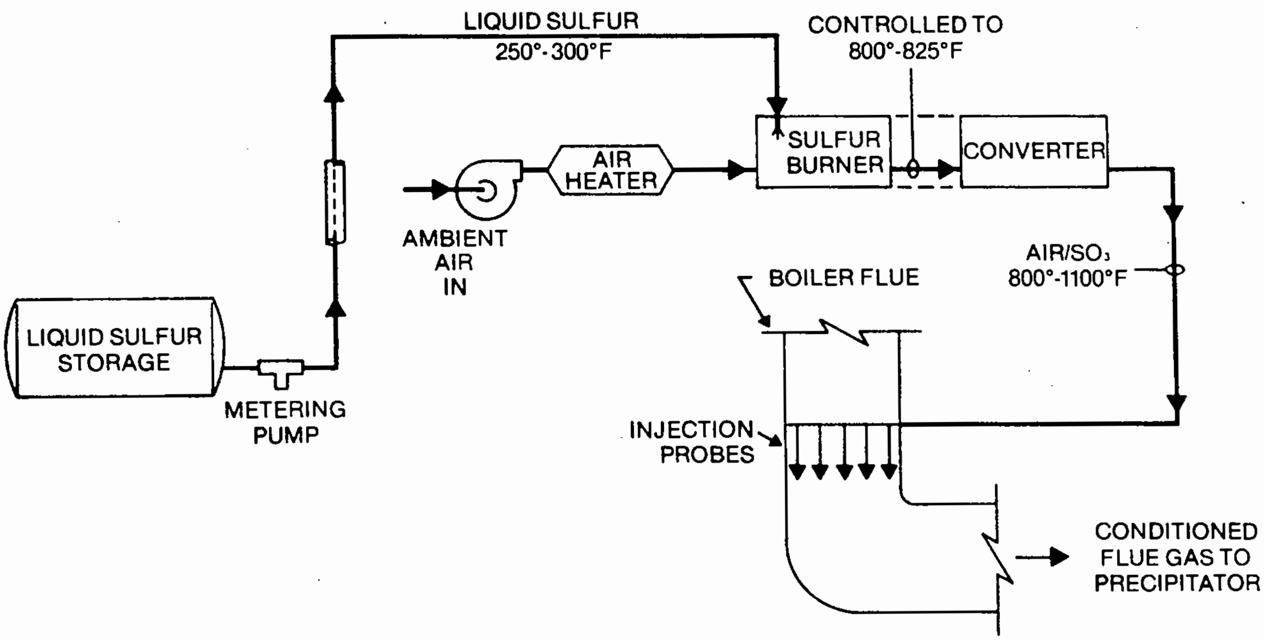


Figure 4.3-24. Flow diagram of sulfur burning flue gas conditioning system.

Courtesy of Robert L. Reveley (Vice President Wahlco, Inc.)

achievable current densities, enhancement of particulate collection efficiencies, and an improvement in fractional efficiency collection capability (see Figure 4.3-25).

Vanadium pentoxide and ferric sulfate have been added to flue gas on an experimental basis as potential catalysts for the formation of SO_3, but neither has given definitive results.

Potassium sulfate, a water-soluble alkalai, is another compound that has been tested in full-scale applications as a conditioning agent for preheating kilns in Brazil in addition to a conditioning tower.[38] An aqueous solution of potassium (0.4% increase in water-soluble K) reduced resistivity from 10^{13} to 10^{11} ohm-cm and improved ESP performance. Additional tests with potassium sulfate and sodium chloride at an ESP installation on a coal-fired lime kiln in South Africa yielded similar results.[38] Sodium chloride is not recommended as a conditioning agent for the cement industry because of the adverse effect of even small amounts of chloride on kiln clinker quality. Addition of dry sodium chloride to the coal being ground for firing in a Danish lime kiln led to considerable improvement in ESP performance.[38]

In summary, flue gas conditioning is often successful in improving ESP performance by reducing dust resistivity or through other mechanisms. Conditioning agents should not be seen as a cure-all for ESP problems, however; they cannot correct problems associated with an underpowered or undersized ESP, poor gas distribution, misaligned plates and wires, or inadequate rapping. Thus, any existing installation should be carefully evaluated to determine that poor ESP performance is due only to high resistivity and not the above-mentioned problems. Conditions for injection of a chemical conditioning agent should also be carefully studied. Inadequate mixing of the conditioner can result in performance below that expected.

4.3.4 Operation and Maintenance of Electrostatic Precipitators

4.3.4.1 Safety Considerations. An important aspect of ESP operation and maintenance is the safety of personnel. Besides the problems and precautions necessary because of confined area entry, the dangers of high voltage must be considered. Even after the power supply has been shut down, a residual charge may be retained by the ESP, which behaves much like a large

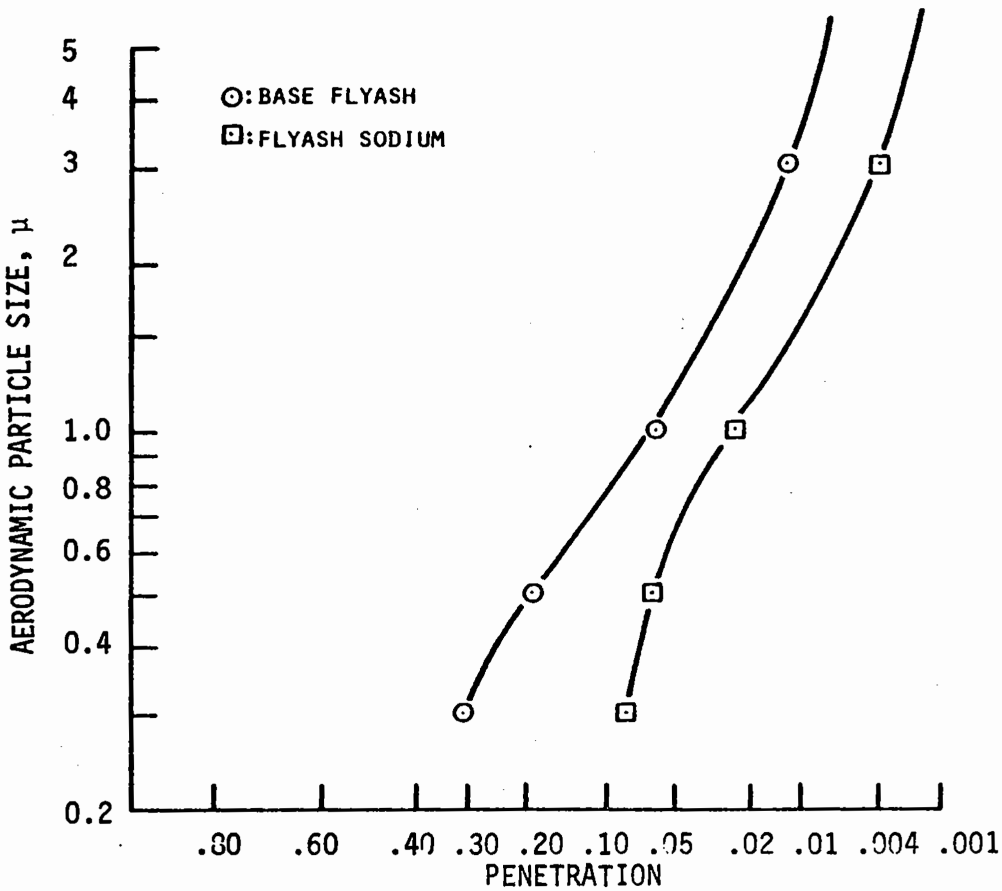


Figure 4.3-25. Comparison of mean penetration results.[37]

capacitor. Prior to entry of personnel into the ESP all safety interlock procedures should be followed so that the ESP, is properly grounded and electrically discharged.

4.3.4.2 Modes of Failure in ESP's. Numerous mechanical and electrical failures can occur in ESP's. Often these failures have synergistic effects that cause other malfunctions. Generally the modes of failure are either mechanical or electrical, although the symptoms of a malfunction may be manifested as both.

The most common problems associated with ESP malfunctions are discharge wire breakage, plugged hoppers causing excess buildup of material, and failure of rappers or vibrators. Other problems are insulator failures, inadequate electrical energization, and changes in the process operation away from the specified design criteria. A brief discussion of the common failures and their effects on emissions is presented below.

4.3.4.2.1 Discharge wires. One of the most common problems associated with suspended wire electrode ESP's is wire breakage, which typically causes an electrical short circuit between the high-tension discharge wire system and the grounded collection plate. The electrical short trips the circuit breaker and disables a section of the ESP, which remains disabled until the broken discharge wire is removed from the unit.

Electrical erosion, the predominant cause of failures, occurs when repeated electrical sparkovers or arcs occur in a localized region. Heating and vaporization of a minute quantity of metal occur with each spark. Sparkover at random locations will cause no serious degradation of the discharge electrode. Repeated sparkover at the same location, however, can remove significant quantities of material, with subsequent reduction of cross-sectional area and ultimate failure at that point.[39]

Localized sparking can be caused by misalignment of the discharge electrode during construction or by variations in the electric field resulting from "edge" effects of adjacent discharge and collection electrodes at the top and bottom of the plates. Measures that will eliminate failure at these points are adding shrouds and providing a round surface at the edge of the collection electrode to reduce the tendency for sparking.[39]

Electrical erosion can also be caused by "swinging" of electrodes, which can occur when the mechanical resonance frequency of the discharge wire and weight system is harmonically related to the electrical frequency of the power supply. The power supply adds energy to the swinging wire, and sparking occurs with each close approach to the collection plate. This action leads to erosion of the electrode and mechanical failure.[39]

Poor workmanship during construction can also cause electrical failure of the discharge electrode. If pieces of the welding electrode remain attached to the collection plate, localized deformation of the electric field can lead to sparking and failure of the discharge electrode.

Mechanical fatigue occurs at points where wires are twisted together, and where mechanical motion occurs continually at one location. This occurs at the top of a discharge electrode where the wire is twisted around the support collar. Methods of reducing mechanical fatigue include selection of discharge electrode material that is resistant to cold work annealing after attachment.

Chemical attack is caused by a corrosive material in the flue gas, which can occur when high-sulfur coal is burned and flue gas exit temperatures are low and near the acid dew point. Use of ambient air to purge insulator compartments also can cause the temperature to drop below the acid dew point in a localized region. Corrosion can be minimized by operation at higher flue gas temperatures or by use of hot, dry air to purge insulator compartments. Use of good insulation around the ESP shell to maintain high temperatures also provides adequate protection within the usual range of operating temperatures and fuel sulfur contents.[39]

Failure of some discharge wires can be expected in all ESP's, although many rigid-frame units experience many fewer problems with discharge wire breakage than do weighted-wire designs. If it occurs in a random manner, this wire breakage will not significantly degrade ESP performance. After a number of wires have broken and have been removed, they will have to be replaced during some scheduled outage. It is important that wire breakage does not occur excessively in any given gas passage between any two plates. Excessive wire breakage will result in ineffective charging and collection of particulate in the passage missing many wires.

4.3.4.2.2 Particulate removal system. Failure of the particulate discharge and removal system will allow material to build up in the gas treatment zone. This buildup of material can cause misalignment of both the collection plates and the discharge electrodes. Arcing between the wires and plates will usually occur. In some applications, collection plates can be warped, as well as discharge wire frames in rigid-frame designs. An outage will be required for repair and realignment of the components since the electrical section would be rendered useless. Buildup of materials also can lead to the formation of clinker-like material between the discharge electrodes and the collection electrodes. This clinker-like material is formed by fusion of the dust when the high voltage of the ESP is passed through it.

Proper design of particulate discharge and removal systems provides the best means of preventing problems. Particulate characteristics such as bulk density, flow characteristics, and agglomeration should be considered in the initial design. Materials are generally more free flowing when hot, and efforts to maintain the wall temperature of the hopper above 200°C will help reduce hopper problems.[31] Insulation of the entire hopper, and windbreaks around the hopper area can add to the available heat in the hopper area. Heaters should be installed from the bottom apex to at least 2 meters high on hoppers on the inlet sections of the ESP and 1 meter high on the outlet fields. Ratings of 6 to 10 W per m^2 of hopper surface area should be satisfactory.[31] Reduction of inleakage through hopper access doors and cleanout ports during and transfer from the hopper to the conveyor mechanism will reduce the effects of cooling and condensation in the hopper as well as reducing the reentrainment of collected dust.

Hoppers often contain baffle plates to prevent gas sneakage or bypassing of the gas stream through the hoppers. Where the baffle plates are close to hopper works, a "bridge" of material can be formed causing a build-up of dust into the gas treatment zone. This problem can be avoided in the design stage.

The use of vibrators on hoppers may cause as many problems as they prevent. If the particulate tends to pack and agglomerate, vibrators may cause hopper bridging rather than preventing it. The feasibility of using hopper vibrators should be decided for each individual application.

4.3.4.2.3 Rappers. In dry removal systems, the dust must be removed from the collection surface periodically. Effective rapping depends upon agglomeration of the material on the plate to minimize reentrainment of the dust. The key to rapping is to avoid excessive rapping.[31]

4.3.4.2.4 Insulator/bushings. Suspension insulators support and isolate the high-voltage parts of an ESP. As mentioned earlier, inadequate pressurization of the top housing of the insulators can cause ash deposits or moisture condensation on the bushings, which may cause electrical breakdown at the typical operating potential of 45 kV dc.

Corrective or preventive measures include inspection of fans that ventilate the top housing, availability of a spare fan for emergencies, and heating of insulators to prevent condensation.

4.3.4.2.5 Electrical energization. Electrical energization must be adequate to charge the particles, maintain the electric field, and hold the collected dust to the collection plates. Among several possible causes of failure to achieve the required level of power input to the ESP, the following are most common:[39]

- High dust resistivity
- Excessive dust accumulation on the electrodes
- Unusually fine particle size
- Inadequate sectionalization
- Improper rectifier and control operation
- Misalignment of electrodes
- Inadequate power supply range.

If a precipitator is operating at a spark-rate-limited condition but current and voltage are low, the problem can commonly be traced to high-resistivity dust, electrode misalignment, or uneven corona resulting from buildup on the discharge electrode. The effects of high resistivity are discussed in more detail in Section 4.3.2 in terms of conditions specific to utility industry, where resistivity presents the greatest problem.

Failures in ESP controls can prevent the system from achieving the level of power required for normal operation. Following are the most common malfunctions in controls:

1. Power failure in the primary system
2. Transformer or rectifier failure in secondary system caused by:
   a) Insulation breakdown in transformer

b) Arcing in transformer between high-voltage switch contacts

c) Leaks or shorts in high-voltage structure

d) Contamination of the insulating field.

The most effective measure for correction of control failures is a good maintenance program in which the controls are checked periodically for proper operation. A daily log of instruments that register current, voltage, and spark rate can also indicate potential problems.

4.3.4.3 Preventive Maintenance Schedule for ESP's.

4.3.4.3.1 Daily maintenance. An accurate log should be kept on all aspects of precipitator operation including electrical data, changes in rapper and vibrator operation, fuel quality, and process operations. Such a log can provide information for diagnostic troubleshooting when any change in performance occurs. For example, it is obvious that gross departures from normal readings on the T-R meter and transmissometer indicate trouble. It is not so widely recognized that small variations, often too slight to be noticed without checking daily readings, can indicate impending trouble.[39]

Problems that usually affect precipitator performance gradually, rather than suddenly, include (1) air inleakage at heaters or in ducts leading to the precipitator, (2) dust buildup on precipitator internals, and (3) deterioration of electronic control components. Such problems are often indicated by a slight but definite drift of daily meter readings away from baseline values.[1]

An operator should usually not try to correct deviant meter readings by adjusting control set points. An automatic control response range should accommodate normal variations in load. When major changes occur, such as would result from firing a coal substantially different from that for which the precipitator was designed, the precipitator manufacturer should be called in to retune the installation.[39] If no such major changes have occurred, then variant meter readings indicate problems that must be detected and corrected. Figure 4.3-26 illustrates a log of electrical readings that are checked several times at a coal-fired utility boiler installation. These readings are used in troubleshooting ESP operations.

Probably 50 percent of all electrical set tripouts are caused by ash buildup. Short of set tripout, buildup above the top of hoppers can cause

PRECIPITATOR LOG SHEET

UNITS 1 & 2

NO. 1 PRECIPITATOR		12 MID	3 A M	6 A M	9 A M	12 NOON	3 P M	6 P M	9 P M
SET 4	PPTR CABLE 1 KV								
	AVG SPARK RATE								
	PPTR CABLE 2 KV								
	TRANS PRI VOLTS V								
	PPTR AVG CURRENT MA								
	TRANS PRI CURRENT								
SET 3	PPTR CABLE 1 KV								
	AVG SPARK RATE								
	PPTR CABLE 2 KV								
	TRANS PRI VOLTS V								
	PPTR AVG CURRENT MA								
	TRANS PRI CURRENT								
SET 2	PPTR CABLE 1 KV								
	AVG SPARK RATE								
	PPTR CABLE 2 KV								
	TRANS PRI VOLTS V								
	PPTR AVG CURRENT MA								
	TRANS PRI CURRENT								
SET 1	PPTR CABLE 1 KV								
	AVG SPARK RATE								
	PPTR CABLE 2 KV								
	TRANS PRI VOLTS V								
	PPTR AVG CURRENT MA								
	TRANS PRI CURRENT								
NO. 2 PRECIPITATOR									
SET 8	PPTR CABLE 1 KV								
	AVG SPARK RATE								
	PPTR CABLE 2 KV								
	TRANS PRI VOLTS V								
	PPTR AVG CURRENT MA								
	TRANS PRI CURRENT								
SET 7	PPTR CABLE 1 KV								
	AVG SPARK RATE								
	PPTR CABLE 2 KV								
	TRANS PRI VOLTS V								
	PPTR AVG CURRENT MA								
	TRANS PRI CURRENT								
SET 6	PPTR CABLE 1 KV								
	AVG SPARK RATE								
	PPTR CABLE 2 KV								
	TRANS PRI VOLTS V								
	PPTR AVG CURRENT MA								
	TRANS PRI CURRENT								
SET 5	PPTR CABLE 1 KV								
	AVG SPARK RATE								
	PPTR CABLE 2 KV								
	TRANS PRI VOLTS V								
	PPTR AVG CURRENT MA								
	TRANS PRI CURRENT								

REMARKS: ______________________________

OPERATORS 12-8 ________ 8-4 ________ 4-12 ________

DATE ________ DAY ________

Figure 4.3-26. Precipitator log sheet.

excessive sparking that erodes discharge electrodes.[1] Further, the forces created by growing ash piles can push internal components out of position, causing misalignment that may drastically affect performance. Sometimes operators attempt to preserve alignment by welding braces to hold collecting-electrode plates in position. This practice may be inadvisable because restraining the plates reduces the effectiveness of the rapping action that keeps them clean.[39]

Although various indicators and alarms can be installed to warn of hopper-ash buildup and of ash-conveyor stoppage, the operator can double check by testing temperature at the throat of the hopper. If the temperature of one or more hoppers seems comparatively low, the hopper heaters may not be functioning properly. Generally, however, low temperature indicates that hot ash is not flowing through the hopper and that bridging, plugging, or failure of an automatic dump valve has held ash in the hopper long enough for it to cool. The ash subsequently will build up to the top of the hopper.[39]

If the temperatures of all hoppers seem low, the ash-conveyor system should be checked; the system may have stopped or dust agglomeration may be so great that the conveyor can no longer handle all of the fly ash.

Hopper plugging is sometimes caused by low flue gas temperature, which permits moisture condensation. The temperature of the gas entering the ESP may be too low, or ambient air may be leaking into the flue gas duct. Hoppers are particularly prone to plugging during startup after an outage, when they are cold and usually damp.

Daily checking of the control room ventilation system minimizes the possibility of overheated control components, which can cause the control set points to drift and can accelerate deterioration of sensitive solid-state devices.

A daily check of all hopper and ESP access doors to detect gas inleakage is recommended. Gas inleakage can cause excessive sparking, corrosion, and particle reentrainment.

4.3.4.3.2 Weekly maintenance. Rapper solenoid-coil failures, fairly common during the period when high voltage was used, are rare with modern low-voltage equipment.[39] Still, a weekly check of all units is advisable. Rapper action should be observed visually, and vibrator operation confirmed by touch. If inadequate rapping force is suspected, an accelerometer mounted on the plates could be used to verify that rapping acceleration is adequate (often, up to 30 G is required). This is best done on a pretest check.

Control sets must be checked internally for deposits of dirt that may have penetrated the control cabinet filter. Accumulation of dirt can cause false control signals and can damage such large components as contactors and printed circuits.

Finally, filters in the lines supplying air to control cabinets and to the precipitator top housing should be checked and cleaned if necessary to prevent plugging.[39]

4.3.4.3.3 Monthly maintenance. Most new precipitators incorporate pressurized top housings that enclose the bushings through which high-voltage connections are made to the discharge electrodes within the precipitator box. Pressurization ensures that if gas inleakage occurs where the bushings penetrate the precipitator hot roof, gas will flow into the precipitator rather than out from it. Leakage from the precipitator into the housing could cause ash deposits or moisture condensation on the bushings, with risk of electrical breakdown at the typical operating potential of 45 kV dc.

Monthly maintenance also should include inspection of bushings visually and by touch for component vibration, checks of differential pressure to ensure good operation of the fan that pressurizes the housing, and manual operation of the automatic standby fan to make sure it is service-ready.

4.3.4.3.4 Quarterly maintenance. Quarterly maintenance includes inspection of electrical-distribution contact surfaces. These should be cleaned and dressed and the pivots should be lubricated quarterly if not more frequently, since faulty contacts could cause false signals.[39] Further, because transmissometer calibration is subject to drift, calibration should be verified to prevent false indications of precipitator performance.

4.3.4.3.5 Semi-annual maintenance. Inspection, cleaning, and lubrication of hinges and test connections should be performed semi-annually. If this task is neglected, extensive effort eventually will be required to free test connections and access doors, often involving expensive downtime.

Performance tests may be required at any time; they should not be delayed while connections are made usable. An effective preventive measure is to recess fittings below the insulation.[39]

Inspection of the exterior for corrosion, loose insulation, surface damage, and loose joints can identify problems while repair is still possible. Special attention should be given to points at which gas can leak out as fugitive emissions.[39]

4.3.4.3.6 Annual maintenance. Scheduled outages must be long enough to allow thorough internal inspection of the precipitator. Following is a summary of items to be checked during an annual inspection, abstracted primarily from Reference 40.

1. Dust accumulation--The upper outside corners of a hopper usually show the greatest accumulation. A spotlight can be used to check for dust buildup, eliminating the need to enter the hopper.

2. Corrosion--Inaccessible parts of the ESP are often attacked by corrosion. Access doors and frames, which are difficult to insulate, are usually attacked first. Condensation can occur in penthouses that contain support insulators; the penthouses are at lower temperatures than the gas, and moisture is added also by purge air from the outside.

Corrosion can occur at several places in the ESP housing--the underside of roof plates, the outside wall, the space between outside collecting surface plates and sidewall, the back of external stiffening members that act as heat sinks, and any area not continuously subject to gas flow such as corners and the upper portion of the hopper connection to inlet and outlet ducts. All gas connections should be checked for inleakage of oil, gas, or air.

Corrosion in these areas can be minimized by keeping interior surfaces hot and by effective thermal insulation of outside surfaces. Use of heaters during routine shutdowns or operation at low loads also may help prevent corrosion.

3. Rappers--Maintenance of the magnetic-impulse, gravity-impact rapper has been discussed. Many of the rigid-wire ESP's, however, have mechanical rappers. The drives for collecting and discharge electrode rappers should be checked for high motor temperature, unusual noise, and level and condition of the lubricant.

Mechanical rappers should be checked for excessive wear, shifting of point of impact, free movement of wire-frame rapper release, free movement of hammers, and wear on hammer shaft bushings.

4. Hoppers--On both weighted-wire and rigid-wire precipitators, the hopper discharge should be checked for such objects as broken pieces of rappers, wires, and scale. Presence of foreign objects indicates a problem that should be investigated further.

5. Gas distribution plates--Although perforated plates usually do not become plugged, uneven distribution can sometimes cause plugging of a portion of the plates. If a rapping system is not used, manual cleaning is required.

6. Discharge electrodes--Frames in rigid-frame, discharge-electrode precipitators should be centered between two rows of collecting surface plates with a maximum deviation of ± 0.6 cm. Discharge wires must be straight and securely connected to the discharge frame.

Weighted-wire precipitators should be checked for missing or dropped weights. Removal of a broken wire that is not replaced should be recorded on a permanent log sheet.[2] In addition the location of broken wires, location on the wire where the break occurred, and the cause of the break, (erosion, corrosion, etc.) should be recorded. Discharge wires should be cleaned manually as required.

7. Collecting electrodes--Collection plates should be inspected for warping due to excessive heat or hopper plugging. Corrosion of lower portions of the plates and portions of plates adjacent to door openings indicates air inleakage through hoppers or around doors.[2] Plates should be cleaned manually as required.

8. Suspension insulators--When insulators become heavily coated with moisture and dust, they may become conductive and crack under high-voltage stress. Cracks can be spotted with a bright light during inspection. Faulty insulators can cause excessive sparking and voltage loss and can fail abruptly or even explode if allowed to deteriorate.

9. Housing--Thick dust deposits on interiors of housings indicate high gas velocities resulting from excessive gas volumes, a condition that should be corrected.

4.3.4.3.7 Situational maintenance. Certain preventive maintenance and safety checks are so important that they should be performed during any outage of sufficient length, without waiting for scheduled downtime. Air load readings should be compared with baseline values to detect possible deterioration in performance. Readings taken immediately upon restoring the precipitator to service can serve as a check on any changes resulting from maintenance done during the outage. All maintenance performed on this situational basis should be recorded for diagnostic purposes.

Critical internal alignments should be checked whenever an outage allows; any misalignment warrants immediate corrective action. Interiors of control cabinets and top housing should be checked during any outage of 24 hours or more and cleaned if necessary. Any outage of more than 72 hours provides an opportunity to check grounding devices, alarms, interlocks, and other safety equipment and to clean insulators and bushings.[39]

4.3.4.4 Optimization of Performance and Energy Consumption.

Preoperational checklist. Before placing the equipment in operation, plant personnel should perform a thorough check and visually inspect the system components in accordance with the manufacturer's recommendations. Some of the major items that should be checked are summarized below:

Control Unit

Proper connections to control

Silicon Rectifier Unit

Rectifier-transformer insulating liquid level

Rectifier ground switch operation

Rectifier high-voltage connections

High-voltage bus transfer switch operation

High-Tension Connections

High-tension bus duct

Proper installation

Installation of vent ports

Equipment Grounding

Precipitator grounded

Transformer grounded

Rectifier controls grounded

High-tension guard grounded

Conduits grounded

Rapper and vibrator ground jumpers in place

4.3.4.4.1 Air load tests. After the precipitator is inspected (i.e., preoperational check adjustment of the rectifier control and check of safety features), the air load test is performed. Air load is defined as energization of the precipitator with minimum flow of air (stack draft) through the precipitator. Before introduction of an air load or gas load (i.e., entrance of dust-laden gas into the precipitator), the following components should be energized:

Collecting plate rappers

Perforated distribution plate rappers

High-tension discharge electrode vibrators

Bushing heaters - housing/compartments

Hopper heaters - vibrators - level indicators

Transformer rectifier

Rectifier control units

Ventilation and forced-draft fans

Ash conveying system

The purpose of the air load test is to establish reference readings for future operations, to check operation of electrical equipment, and to detect any improper wire clearances or grounds not detected during preparation inspection. Air load data are taken with the internal metal surfaces clean. The data consist of current-voltage characteristics at intervals of roughly 10 percent of the T-R milliamp rating, gas flow rate, gas temperatures, and relative humidity.

For an air load test, the precipitator is energized on manual control. The electrical characteristics of a precipitator are such that no sparking should occur. If sparking does occur, an internal inspection must be made to determine the cause. Usually, the cause is (1) close electrical clearances and/or (2) the presence of foreign matter that has been left inside the precipitator.

After the precipitator has been in operation for some time, it may be necessary to shut it down to perform internal inspections. At such times, it would be of interest to take air load data for comparison with the original readings.

4.3.4.4.2 Gas load tests. The operation of a precipitator on gas load differs considerably from operation on air load with respect to voltage and current relationships. The condition of high current and low voltage characterizes the air load, whereas low current and high voltage characterize the gas load. This effect governs the operation of the precipitator and the final setting of the electrical equipment.

4.3.4.5 ESP Startup Procedures. The exact startup procedures for any ESP are dependent upon the application and the manufacturers' recommended procedures. The following general guidelines are usually applicable.

Prior to startup it should be confirmed that the hoppers are empty before closing all hatches. Any lumps of material that may impede the flow of dust should be removed. Several hours before process startup the hopper heater should be turned on so that hoppers are warm.

Insulator surfaces should be heated by early startup of insulator heaters or by the purge air system to prevent electrical tracking over the surface of the insulators.

The point at which the ESP is energized will depend upon the individual application. Some processes can be started up with the ESP fully energized, whereas others have explosive gas compositions that must be considered. Generally, the temperature at each field is higher than the moisture dew point before that field is energized to minimize sparking.

It is usually recommended that the ESP be energized under manual control to reduce spark-over during startup and that the power supplied to each section be increased gradually. Newer automatic controls that sense the spark-over threshold can be set to spark-limit mode and placed on automatic control. As the temperature and the process stabilize, the controller will bring the power level to its maximum control level.

Rappers should be turned off through the process startup and probably for a period of time after the ESP is energized to allow formation of an adequate layer of dust on the plates. The amount of time between startup and rapper initiation will depend upon the application and on previous experience.

4.3.4.6 Normal Operation. Although electrical portions of a precipitator require very little maintenance, the items enumerated below should be attended regularly if the equipment is to give optimum service. It is considered good practice to assign one plant operator on each shift the task of checking and recording data on electrical equipment at the start of the shift.

The cycle of inspection and maintenance during normal operation includes the following components:

T-R sets and associated equipment and controls

Transformer enclosure

Pipe and guard

Vibrators

Plate rappers

Top housing

Insulator compartments

Upper high tension frame

Discharge wires

Collecting plates

Lower precipitator steadying frame

Dust collection point (dry or wet bottom)

Hoppers and screw conveyors

Precipitator shell.

4.3.4.6.1 Using T-R set meters for troubleshooting. An operator can utilize the meters to aid in diagnosing other problems with an ESP. General examples of the effect of changing conditions in the gas stream and within the ESP on control set meters are presented below:[40]

1. When the gas temperature increases, the voltage will increase and the current will decrease. Arcing can develop. When the gas temperature decreases, the voltage will decrease and the current will increase.

2. When the moisture content of the gases increases for any given condition, the current and voltage will also tend to increase in value.

3. If reduced voltage occurs because of a spark-over, a rise in moisture may allow for an increase in the precipitator voltage level.

4. An increase in the concentration of the particulate will tend to elevate voltages and reduce current flow.

5. A decrease in the particle size will tend to raise voltage while suppressing current flow.

6. A higher gas velocity through the precipitator will tend to raise voltages and depress currents.

7. Air inleakage may cause spark-over in localized areas, resulting in reduced voltages.

8. A number of precipitator fields in series will show varying readings, with voltage-current ratio decreasing in the direction of gas flow.

9. If a hopper fills with dust causing a short, the voltage will be drastically reduced and the current will increase.

10. If a discharge electrode breaks, violent arcing can be observed, with the meters swinging between zero and normal.

11. If a transformer-rectifier unit shorts, voltage will be zero at a high current reading.

12. If a discharge system rapper fails, the discharge wires build up with dust; the voltage increases to maintain the same current level.

13. If a plate rapper fails, the voltage decreases to maintain a current level under sparking conditions.

Table 4.3-3 presents specific examples of the effect of changing conditions on ESP control set readings. The operator can use T-R set readings along with other systematic inspection procedures to optimize performance of an ESP.

4.3.4.6.2 Use of ESP performance curves. Although ESP collection efficiency is reduced by malfunctions such as breakage of discharge wires and deterioration of power supply components, rectifiers, insulators, and similar equipment, a unit can often be kept in compliance with particulate emission regulations by reducing its load. Figure 4.3-27 (top graph) illustrates collection efficiency of a four-field utility ESP with 24 bus sections as a function of the gross boiler load, depending on the number of bus sections out and whether they are in series or parallel. The bottom graph shows the efficiency needed by the ESP to meet a state regulation of 0.38 lb/10^6 Btu as a function of the ash content of coal (assuming a heating value of 11,000 Btu/lb).

These types of graphs can be helpful to the operator. Knowing the ash content of the coal he is firing and knowing which bus sections of his ESP

TABLE 4.3-3. EXAMPLE EFFECTS OF CHANGES IN NORMAL OPERATION ON ESP CONTROL SET READINGS[7]

Condition	Effect	Primary voltage V, a.c.	Primary current A, a.c.	Secondary current mA, d.c.
1. Normal full load		300	50	200
2. System load fall by 1/2	Gas volume and dust concentration decrease, resistance decreases	260	55	230
3. System load constant, but increase in dust load	Resistance increases	350	40	175
4. Gas temperature increases	Resistance rises, sparking increases because of increased resistivity	300-350	50-60	20-250
5. Gas temperature decreases	Resistance decreases	280	52	210
6. ESP hopper fills with dust	Resistance decreases	180	85	300
7. Discharge electrode breaks	Resistance may fall to 0 (may vary between 0 and normal if top part of electrode is left swinging inside the ESP). Violent instrument fluctuations. Arcing can be heard outside the ESP.	0-300	0-50	0-200
8. Transformer rectifier shorts	No current passes from T-R set to the ESP	0	100+	0
9. Discharge system rapper fails	Dust builds up on discharge electrodes. Resistance increases because corona discharge decreases. Additional voltage required to keep current constant.	330	50	200
10. Collection plate rapper fails	Sparking increases. Voltage must be reduced to keep current constant	265	50	200

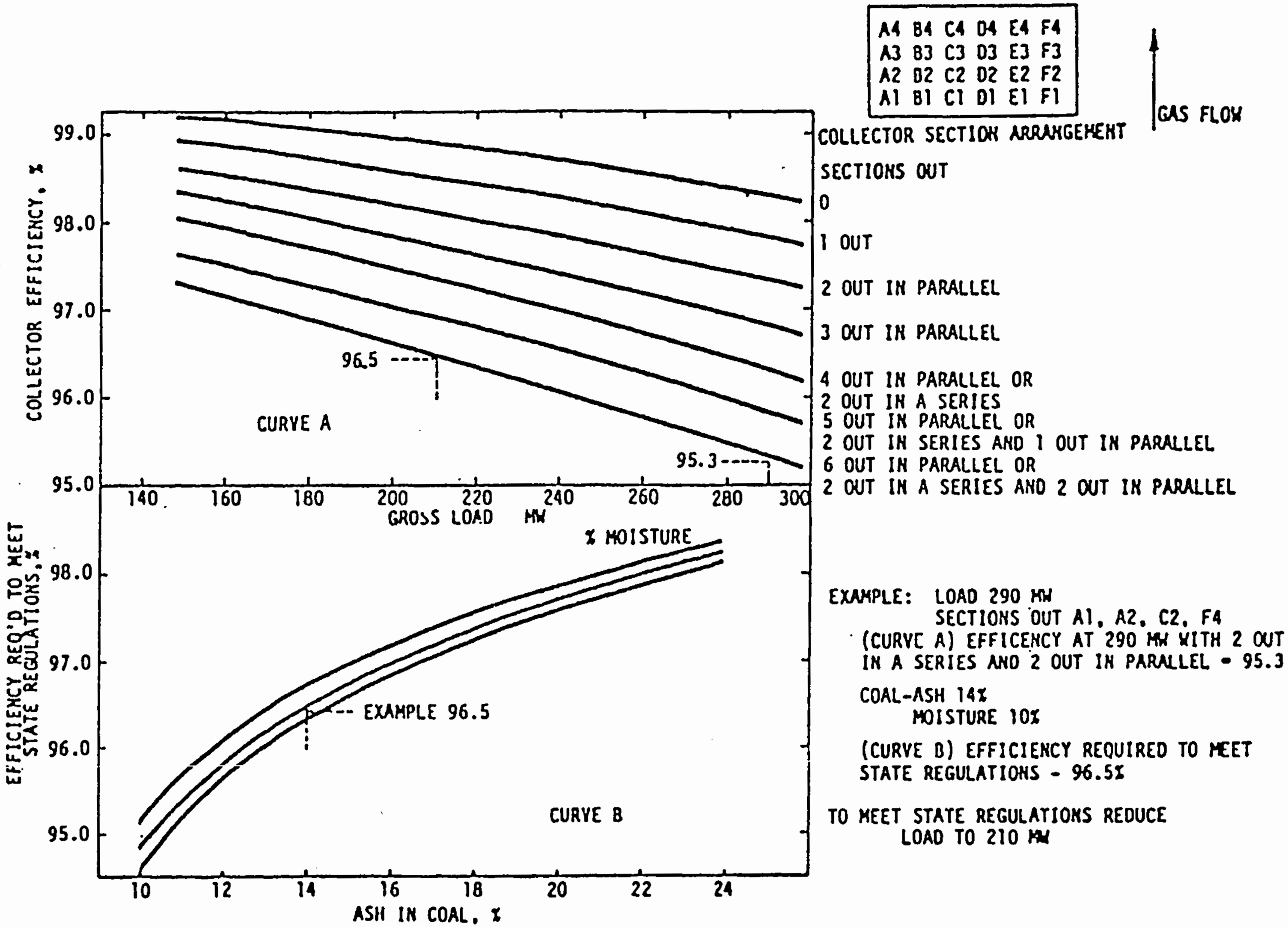


Figure 4.3-27. Typical operating curve to meet emission regulations with partial malfunctions of ESP.[2]

are inoperative, he can tell from the top graph how much the boiler load must be reduced to keep emissions in compliance with regulations. Charts of this type should be developed for each boiler-ESP combination.

4.3.4.6.3 ESP shutdown procedures. ESP shutdown procedures will impact upon the success of maintaining deposits on the collection surface at a workable and acceptable thickness.[31] It is necessary to keep materials from hardening on plates yet maintain acceptable stack conditions during this period. The exact procedures must be determined on an individual basis.

Methods to accomplish maximum cleaning include reducing of air flow through the unit while reducing power to the ESP. Rappers are kept at normal settings. Gradually the fields are deenergized as the fields are cleaned. The last fields of the ESP are kept energized while the system cools and captures most of the reentrained dust.[31]

Hopper evacuation should remain on at least 1 hour after all rappers are shut off and 2 to 3 hours after the fans have been shut down to remove all dust. The object is to remove the dust when it's easiest, i.e., when the temperature is still above 200°C.[31]

After cold shutdown of the ESP, the unit may be entered according to safety interlock procedures incorporated in that particular unit. All safety recommendations and procedures should be followed.

REFERENCES

1. Smith, Wallace B. et al. Procedures Manual for Electrostatic Precipitator Evaluation. Southern Research Institute. Birmingham, Alabama. EPA-600/7-77-059. June 1977.

2. Szabo, M.F. and R.W. Gerstle, Operation and Maintenance of Particulate Control Devices on Coal-Fired Utility Boilers. PEDCo Environmental, Inc. EPA-600/2-77-129. July 1977.

3. A.P. deSeversky, U.S. Patent 3,315,445 April 25, 1967.

4. Jaasund, S.A. and M.R. Mazer, "The Application of Wet Electrostatic Precipitators for the Control of Emissions from Three Metallurgical Processes," presented at symposium entitled Particulate Collection Problems Using Electrostatic Precipitators in the Metallurgical Industry, June 1-3, 1977.

5. Gooch, J.P. and A.H. Dean, "Wet Electrostatic Precipitator System Study," SRI, Birmingham, Alabama, EPA-600/2-76-142, PB 257 128, May 1976.

6. McIlvaine Electrostatic Precipitator Manual, Chapter VI, Section L, August 1976, p. 5613.

7. Oglesby, Sabert, Jr., and Grady B. Nichols. Electrostatic Precipitation. In: Air Pollution, 3rd Edition, Vol. IV. Engineering Control of Air Pollution. Academic Press. New York, San Francisco, London. 1977. pp. 189-256.

8. Portius, D.H., et al. Fine Particle Charging Experiments. Southern Research Institute. EPA-600/2-77-173. August 1977.

9. Sproull, W.T. (title) APCA Volume 22, p. 181. 1972 (as presented in Reference 8).

10. Spencer, Herbert W., III. Rapping Reentrainment in a Nearby Full-Scale Pilot Precipitator. EPA-600/2-76-140. May, 1976.

11. Gooch, J.P. and G.H. Marchant, Jr. Electrostatic Precipitator Rapping Reentrainment and Computer Model Studies. Southern Research Institute. EPRI FP-792, Volume 3. Final Report August, 1978.

12. White, H.J. Electrostatic Precipitation of Fly Ash, Part II, Journal of the Air Pollution Control Association. February 1977.

13. Bickelharyst, R.E. Journal of the Air Pollution Control Association. 1974.

14. McDonald, Jack R. A Mathematical Model of Electrostatic Precipitation (Revision I) Volume 1, Modeling and Programming. Southern Research Institute EPA-600/7-78-111A, June 1978.

15. Ensor, et al. Evaluation of the George Neal No. 3 Electrostatic Precipitator. Meteorology Research, Inc. and Stearns Roger, Inc. prepared for Electric Power Research Institute. EPRI FP-1145. August 1979.

16. Szabo, M.F., and R.W. Gerstle. Operation and Maintenance of Particulate Control Devices in Kraft Pulp Mill and Crushed Stone Industries. PEDCo Environmental, Inc. EPA-600/2-78-210, October, 1978.

17. White, H.J. Electrostatic Precipitation of Fly Ash, Part III. Journal of the Air Pollution Control Association. March 1977.

18. Frisch, N.W., and D.W. Coy. Specifying Electrostatic Precipitators for High Reliability. In: Symposium on Electrostatic Precipitators for the Control of Fine Particles, pp. 131-157. EPA-650/12-75-016, January 1975.

19. Matts, S. and P.O. Ohnfeldt. Efficient Gas Cleaning with S.F. Electrostatic Precipitators. Flakt, A.B., Svenska Flakt Iabricken, June 1973.

20. Feldman, P.L. Effects of Particle Size Distribution on the Performance of Electrostatic Precipitators. Research Cottrell, Inc. Bound Brook, New Jersey. Presented at the 68th Annual Meeting of the Air Pollution Control Association. June 15-20, 1975. No. 75-02-3.

21. Cooperman, P. and G.D. Cooperman. Precipitator Efficiency for Lognormal Distributions. In: Symposium on the Transfer and Utilization of Particulate Control Technology. EPA-600/7-79-044a. February, 1979.

22. Schneider, G.E. et al. Selecting and Specifying Electrostatic Precipitators. Enviro Energy Corp. Chemical Engineering, May 26, 1975, pp. 94-108.

23. Hall, H.J. Design and Application of High Voltage Power Supplies in Electrostatic Precipitation. In: Symposium on Electrostatic Precipitators for the Control of Fine Particles. pp. 159-189. EPA-650/2-75-016, January 1975.

24. Hall, H.J. Design, Application, Operation and Maintenance Techniques for Problems in the Electrical Energization of Electrostatic Precipitators. In: Proceedings - Operation and Maintenance of Electrostatic Precipitators, Michigan Chapter - East Central Section Air Pollution Control Association. April 1978. pp. 19-34.

25. Diulle, Walter, Precipitator Performance Hinges on Control. Envirotech Corporation Power, January, 1975, p. 24.

26. McIlvaine Electrostatic Precipitator Manual, Chapter VI, Section L, August, 1979, p. 5613.

27. Air Pollution and Industry. Van Nostrand Rheinhold Company, New York, 1972. R.D. Ross, Editor.

28. Ito, R. and K. Takimoto. Wide Spacing E.P. is Available In Cleaning Exhaust Gases from Industrial Sources. In: Symposium on the Transfer and Utilization of Particulate Control Technology. Volume 1: Electrostatic Precipitators. EPA-600/7-79-044a. February, 1979.

29. Allen Sherman Hoff Company. A Primer on Ash Handling Systems. 1976.

30. White, H.J. Electrostatic Precipitation of Fly Ash, Part IV. Journal of the Air Pollution Association. April 1977.

31. Katz, J. The Art of Electrostatic Precipitation, 1978.

32. Engelbrecht, H.L. Air Flow Model Studies for Electrostatic Precipitators. In: Symposium on the Transfer and Utilization of Particulate Control Technology: Volume I - Electrostatic Precipitators. Industrial Environmental Research Laboratory. Office of Energy, Minerals, and Industry. EPA-600/7-79-044a. February 1979.

33. Lynch, J.G., and D.S. Kelly. A Review of Rapper System Problems Associated with Industrial Electrostatic Precipitators. Air Correction Division, UOP, Inc. In: Proceedings Operation and Maintenance of Electrostatic Precipitators. Michigan Chapter - East Central Section, Air Pollution Control Association. April 1978. pp. 46-61.

34. PEDCo Environmental, Inc. Data from IGCI manufacturers used in: Design Considerations for Particulate Control Equipment. Prepared under contract for the U.S. Environmental Protection Agency. December 1979.

35. Dismukes, E.B. Flue Gas Conditioning in Coal Fired Power Plants in the United States. In: Second US/USSR Symposium on Particulate Control EPA-600/7-78-037 March, 1978.

36. Lederman, P.B. et al. Chemical Conditioning of Fly Ash for Hot Side Precipitation. In: Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. I, Electrostatic Precipitators, pp. 79-98. EPA-600/7-79-044a. February, 1979.

37. Schliesser, S.P. Sodium Conditioning Test with EPA Mobile ESP. In: Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. I, Electrostatic Precipitators, pp. 205-240. EPA-600/7-79-044a. February, 1979.

38. Peterson, H.H. Conditioning of Dust with Water Soluble Alkali Compounds. In: Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. I, Electrostatic Precipitators, pp. 99-112. EPA-600/7-79-004a. February, 1979.

39. Bibbo, P.P., and M.M. Peacos. Defining Preventive Maintenance Tasks for Electrostatic Precipitators, Research Cottrell, Inc. Power. August 1975, pp. 56-58.

40. Engelbrecht, H.L. Plant Engineer's Guide to Electrostatic Precipitator Inspection and Maintenance, Air Pollution Division of Wheelabrator Frye, Inc., Plant Engineering. April 1976, pp. 193-196.

4.4 FABRIC FILTERS

This section addresses the basic operating principles, design criteria, and operation and maintenance practices for major types of commercially available fabric filters. The particle collection mechanisms of fabric filtration include inertial impaction, Brownian diffusion, interception, gravitational settling and electrostatic attraction. Particles are collected either on a dust cake supported on a fabric or on the fabric itself.

4.4.1 Types of Fabric Filters

Although the basic particle collection mechanisms utilized in various fabric filters are relatively similar, the equipment geometry and mode of fabric cleaning are exceptionally diverse. This diversity is partially due to the broad applicability of these devices, which demands various performance capabilities and physical characteristics. Diversity of fabric filters also results from the individual contributions of numerous equipment and fabric vendors.

Although fabric filters can be classified a number of ways, the most common way is by method of fabric cleaning. The three major categories of fabric cleaning methods are mechanical shaking, reverse air cleaning, and pulse jet cleaning.

4.4.1.1 Mechanical Shaking. A conventional shaker-type fabric filter is shown in Figure 4.4-1. Particulate-laden gas enters below the tube sheet and passes from the inside bag surface to the outside surface. Particles are captured on a cake of dust that gradually builds up as filtration continues. At regular intervals a portion of this dust cake must be removed to enhance gas flow through the filter. The dust cake is removed manually on small systems and mechanically on larger systems. Mechanical shaking of the filter fabric is normally accomplished by a rapid horizontal motion induced by a mechanical shaker bar attached at the top of the bag. The shaking creates a standing wave in the bag and causes flexing of the fabric. The flexing causes the dust cake to crack, and portions are released from the fabric surface. Some of the dust remains on the bag surface and in the interstices of the fabric. The cleaning intensity is controlled by bag tension and by the amplitude, frequency, and duration of shaking. The

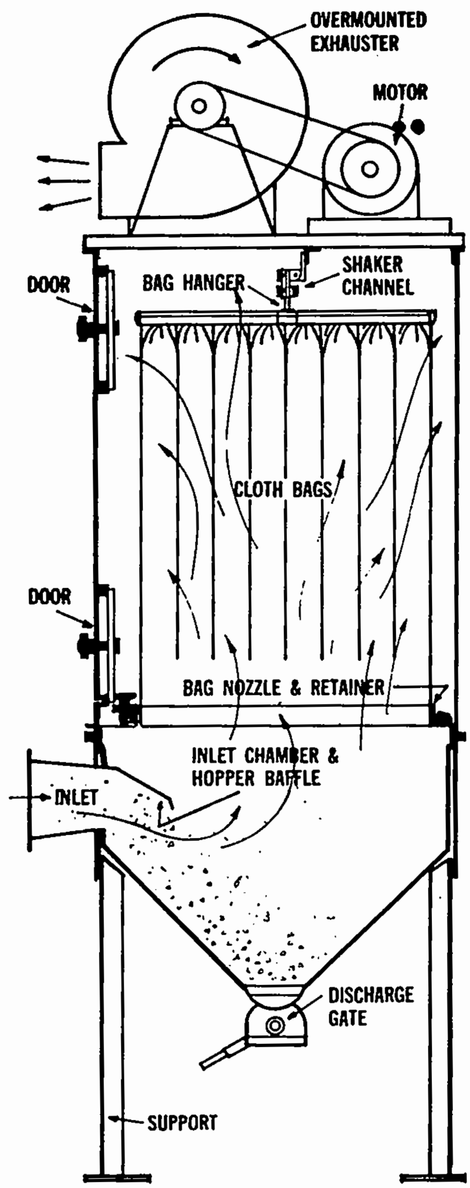


Figure 4.4-1. Small shaker-type baghouse (courtesy of Carborundum Division of Flakt, Inc.)

residual dust cake provides a minimal resistance to gas flow, causing a static pressure drop that is higher than that of a new clean fabric. Woven fabrics are used in shaker-type collectors. Because of the low cleaning intensity, the gas flow is stopped before cleaning to eliminate particle reentrainment and allow dust cake release. The cleaning may be done by bag, row, section, or compartment.

Gas flow through shaker-type fabric filters is usually limited to a low superficial velocity of less than 1 m/min. This means that the total gas flow rate (at operating temperature and pressure) divided by the total cloth area available should not exceed the stated "velocity." This parameter is usually referred to as the air-to-cloth (A/C) ratio and is expressed in m^3/m^2-min. High A/C values may lead to excessive particle penetration or blinding, which reduces fabric life.

Mechanical shaker-type units differ with regard to the shaker assembly design, bag length and arrangement, and type of fabric. All sizes of control systems can use the shaker design.

4.4.1.2 Reverse Air Cleaning. Particles can be collected on a dust cake on either the inside or outside of the bag. A small cylindrical unit with external surface filtering is shown in Figure 4.4-2. In this design the bags are arranged radially and are suspended from an upper cell plate. The inner and outer row reverse-air manifolds rotate around the unit and stop at each bag to induce reverse flow. In this manner the entire baghouse need not be temporarily isolated to allow dust-cake removal. A reverse air panel filter is shown in Figure 4.4-3. The reverse air cleaning manifold traverses the rows of filter panels, cleaning all six layers simultaneously. A somewhat larger reverse air filter is shown in Figure 4.4-4.

Regardless of design differences, reverse-air cleaning is accomplished by reversal of the gas flow through the filter media. The change in direction causes the surface contour of the filter surface to change (relax) and promotes dust-cake cracking. The flow of gas through the fabric assists in removal of the cake. The reverse flow may be supplied by cleaned exhaust gases or by a secondary fan supplying ambient air.

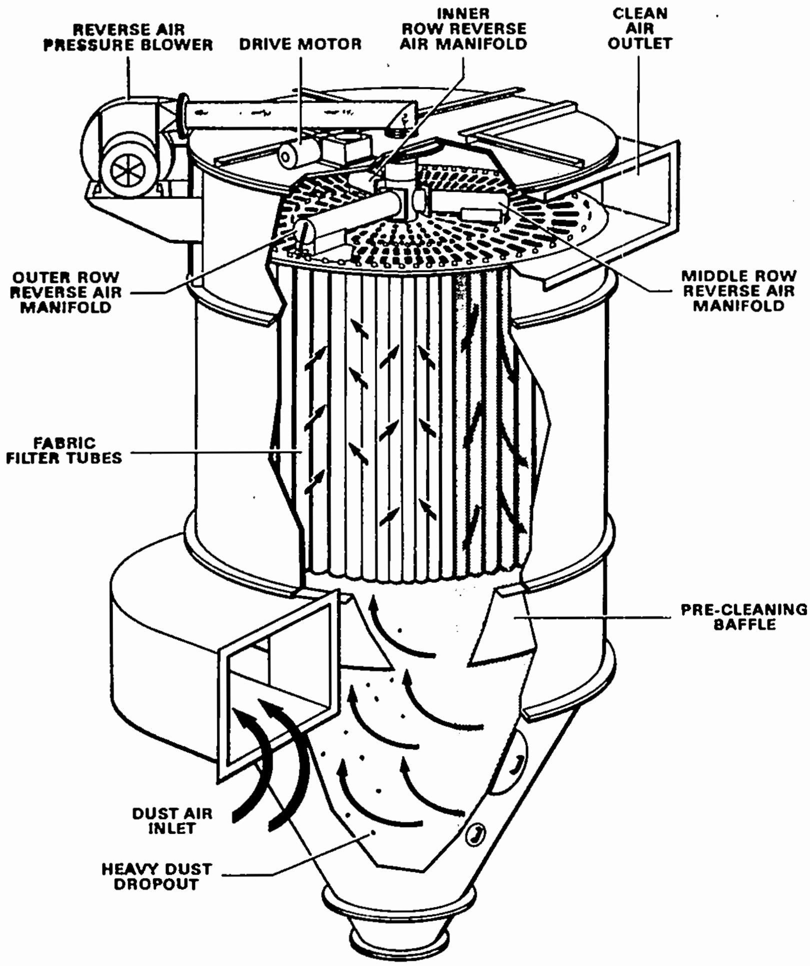


Figure 4.4-2. Reverse-air baghouse (courtesy of Carter-Day Company).

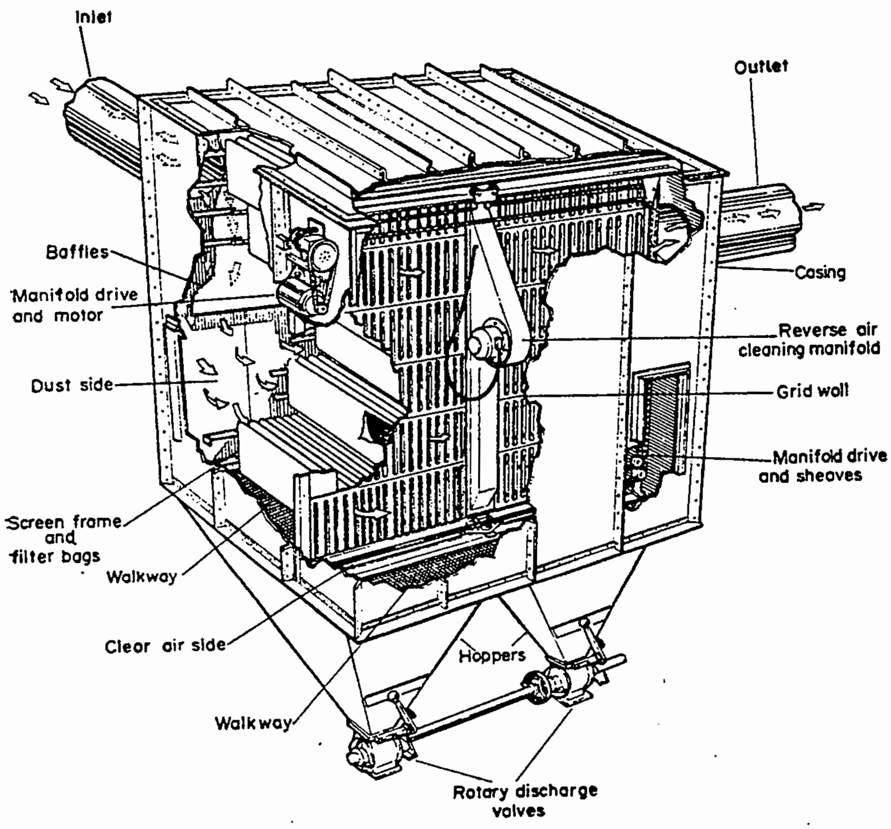


Figure 4.4-3. Continuous reverse air-cleaning system for flat filter sleeves (courtesy of Flakt, Inc.).

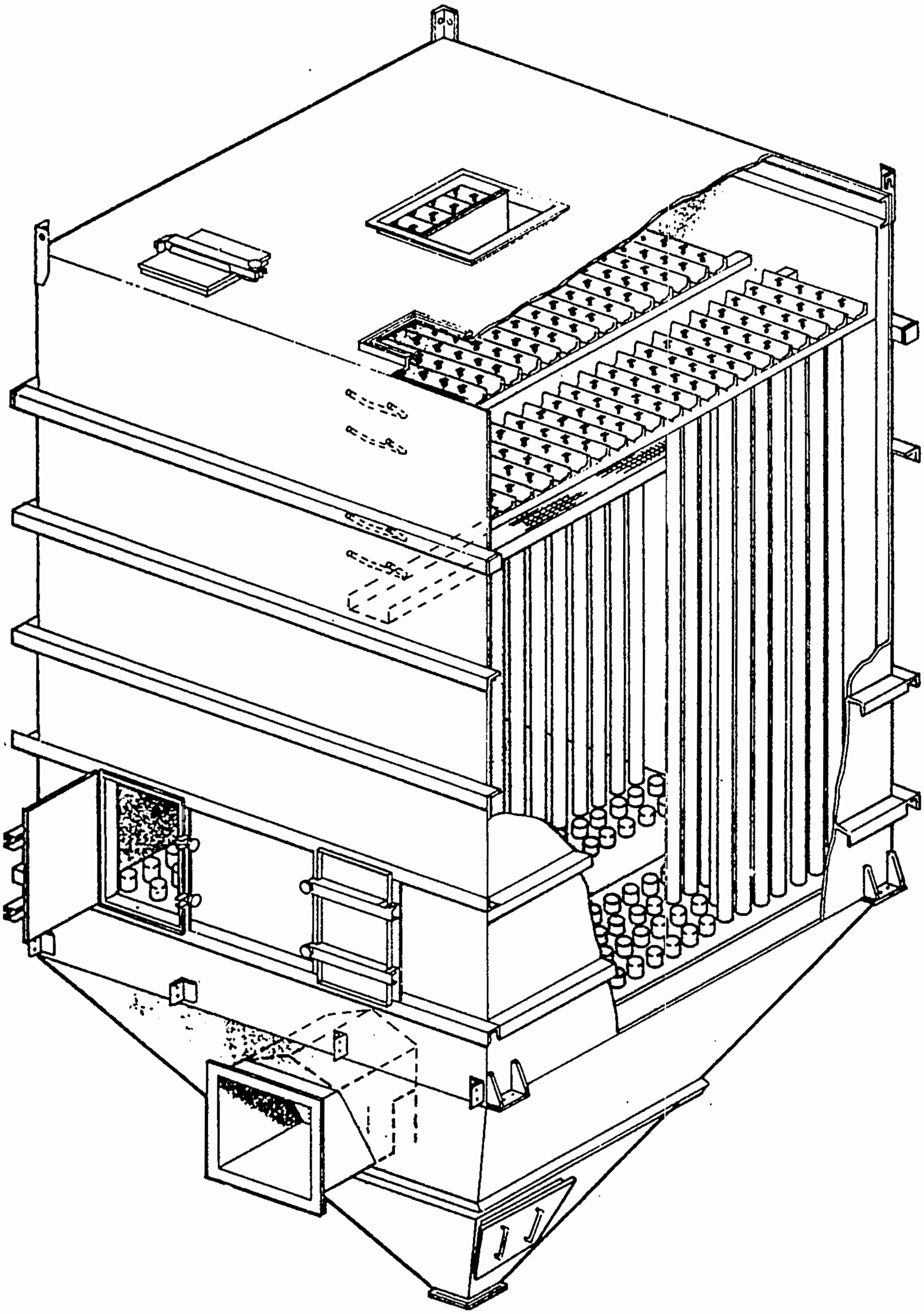


Figure 4.4-4. Reverse-air collector.
(Courtesy of MikroPul Corporation)

In filters with internal cake collection, cleaning is accomplished during off-line operation with compartments isolated. The filter bag may require anti-collapse rings to prevent closure of the tube and dust bridging. Cake release may be increased by rapid reinflation of the bag, creating a snap in the surface, followed by a short period of reverse air flow. Fabrics in reverse-air collectors may be woven or felt. The felts are normally restricted to external surface collection.

Reverse-air filters are usually limited to A/C ratios of less than 1.0 m^3/m^2-min, but the ratio may be higher in certain applications. Most high-temperature (>250°C) baghouses are of this type.

4.4.1.3 Pulse-Jet Cleaning. On pulse-jet fabric filters, particle capture is achieved partially on a dust cake and partially within the fabric. Filtering is done on exterior bag surfaces only. A small pulse-jet baghouse is illustrated in Figure 4.4-5; this device is typical of many small installations. The bags, supported by inner retainers (sometimes called cages), are suspended from an upper cell plate. Compressed air is supplied through a manifold-solenoid assembly (not shown) into the blow pipes shown in an end view. Venturis mounted in the bag entry area are intended to improve the jet pump effect. The classifier shown at the gas inlet is intended to prevent large particles from abrading lower portions of the bag.

A sudden blast of compressed air is injected into the top of the bag. The blast of air creates a traveling wave in the fabric, which shatters the cake and throws it from the surface of the fabric. The cleaning mechanism is classified as fabric flexing and with some degree of reverse air flow. Felted fabrics are normally used in pulse-jet-cleaned collectors, and the cleaning intensity (energy) is high. The cleaning normally proceeds by rows, all bags in the row being cleaned simultaneously. The compressed gas pulse, delivered at 550 to 800 kPa results in local reversal of the gas flow. The cleaning intensity is a function of compressed gas pressure. Pulse-jet units can operate at substantially higher A/C ratios than the types previously discussed. Typical ratio ranges are 1.5 to 3.0 m^3/m^2-min.

The plenum pulse cleaning method is a variation of the pulse-jet cleaning mechanism; in this method an entire section of bags is pulsed with a blast of compressed gas from the clean air plenum. The intensity of plenum

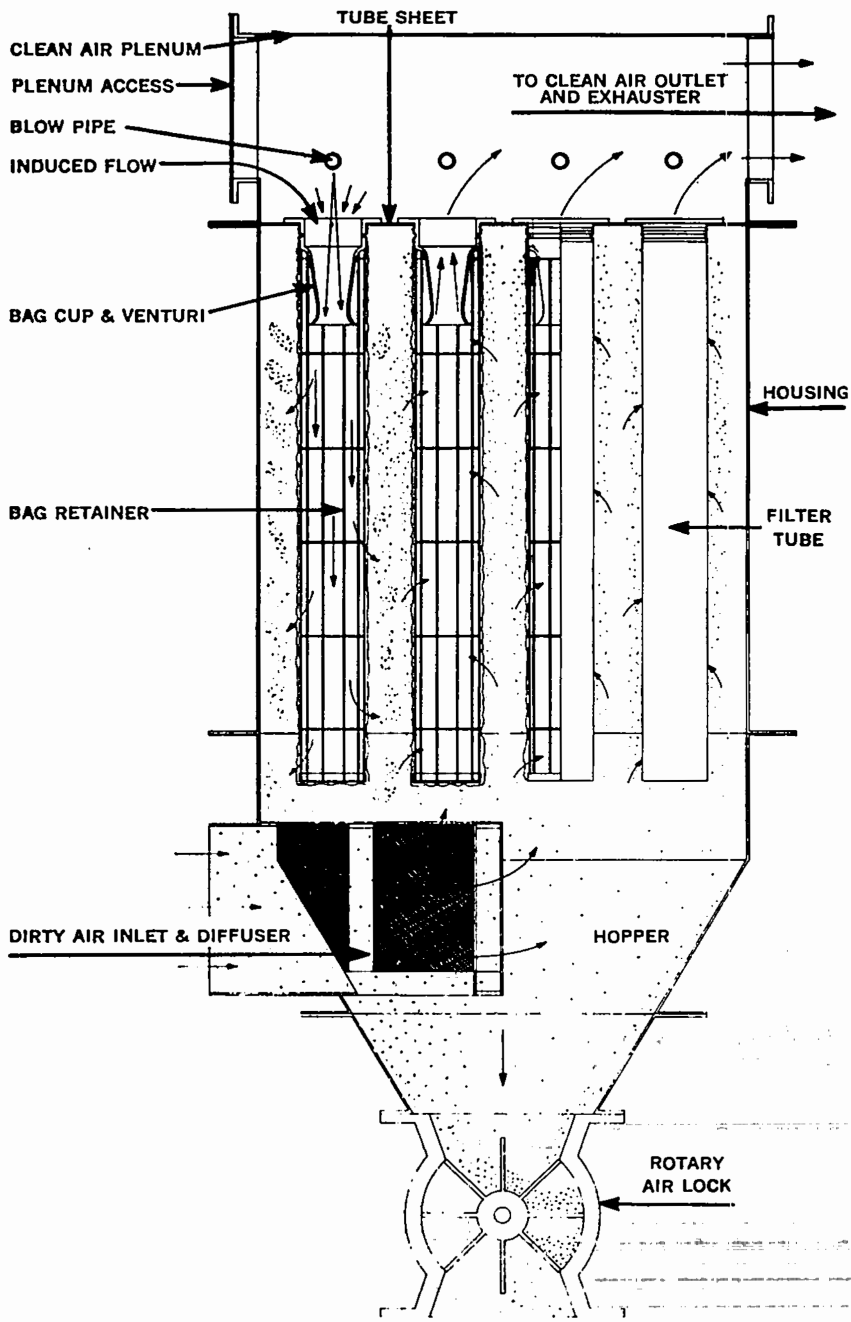


Figure 4.4-5. Pulse jet baghouse (courtesy of George A. Rolfes Company).

4.4.2 Operating Principles of Fabric Filters

The two factors of basic importance in fabric filter operation are particle capture and static pressure loss. Particle capture mechanisms on a microscopic level are not fully understood. Macroscopic behavior, the net result of all microscopic processes, indicates that fabric filter collection is not highly size-dependent as would be expected in view of the collection mechanisms. The static pressure loss results from forcing the gas stream through the fabric and dust cake.

4.4.2.1 Particle Capture. Pore sizes (open areas) of the woven fabric through which the contaminated gas stream passes (open areas) range from 10 to 100 μm, depending on fabric construction and fiber characteristics.[1] Initially the particles easily penetrate this filter. As cleaning continues, some particles are retained upon filter elements (normally fibers) because of the combined action of the classified collection mechanisms shown in Figure 4.4-6.[2] This figure is a simple modification of the mechanism diagrams of Figures 4.1-5, 4.1-6, and 4.1-7. As the dust cake builds up, additional "targets" are available to collect particles; accordingly, penetration drops to very low levels.

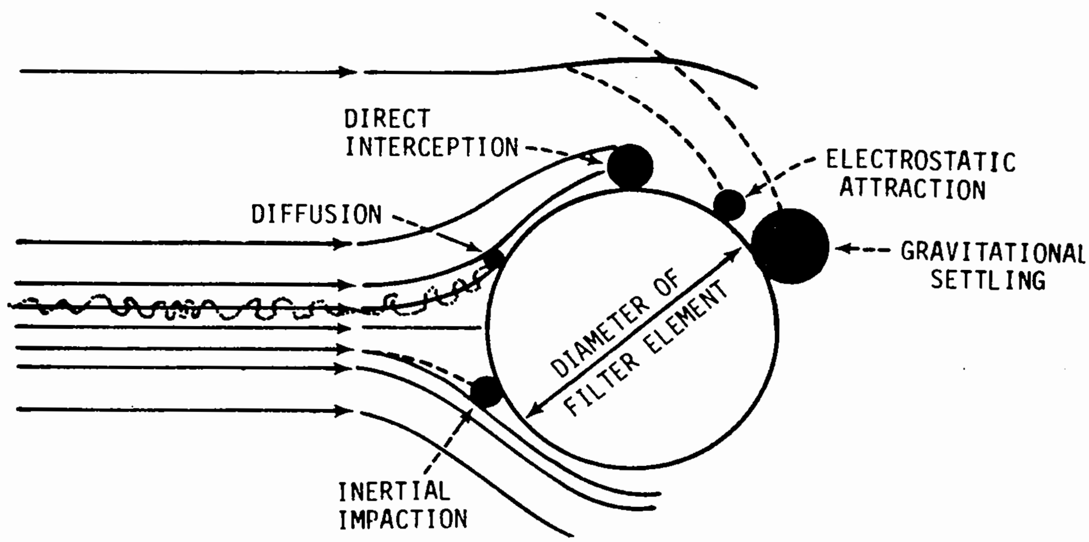


Figure 4.4-6. Initial mechanisms of fabric filtration (courtesy of CRC Press, Inc. Theodore, Louis and Anthony J. Buonicore. Industrial Air Pollution Control Equipment for Particulates. 1976).

Within the dust cake, inertial impaction is the dominant collection mechanism. The forward motion of the particles results in impaction on fibers or on already deposited particles.[2,3] Although increasing gas velocities favor impaction, they reduce the effectiveness of Brownian diffusion. Increasing the fabric porosity also reduces diffusional deposition.[4] Gravity settling of particles as a method of collection is usually assumed to be negligible.[2] This effect should be considered at low velocities, however.[4,5] Electrostatic forces may affect collection; however, the impact on commercial-scale equipment is not fully understood.[6] The magnitude of the electrical charges may depend relative humidity.[6] The source of the charges could be triboelectric interaction between the particles and the fabric or triboelectric interaction before the particles reach the fabric[6 - 9] Donovan, et al.[6] have concluded that the latter is more important.

The net result of the particle collection mechanisms is potentially high-efficiency removal and a penetration curve of the types presented by Turner[10] in Figures 4.4-7 and 4.4-8. These data indicate only a weak particle size dependence. The form of the curve is confirmed by data in Figure 4.4-9 from a shaker type fabric filter (silicon-graphite coated fiberglass bags) serving a spreader stoker boiler.[11] The penetration value scale does not exceed 0.01 so that the shape of the curve can be illustrated.

Dennis and Klemm have proposed that leaks through unblocked pores of 100 to 200 μm in diameter in woven fabrics are partially responsible for the lack of a strong particle size dependence evident in filters using woven fabrics.[12,13]

A direct relationship between penetration and woven fabric pore concentration was observed by Hall, Dennis, and Surprenant.[14] Gas velocities through the pores may be several orders of magnitude above the average face velocity.[14]

The particulate matter emission rate through the pores should be a function of the inlet gas mass loading and the air-to-cloth ratio. The latter determines the actual velocity through the pores. Figure 4.4-10 illustrates the relationship between face velocity and outlet concentration from a series of bench-scale tests. Hall, et al.[14] conclude that the higher emissions at the higher air-to-cloth ratios are attributable to particle reentrainment through pinholes.

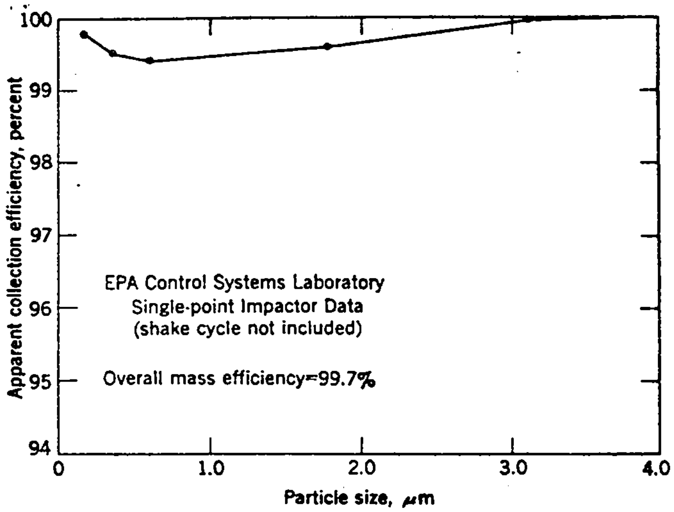


Figure 4.4-7. Baghouse performance, lead sinter machine.

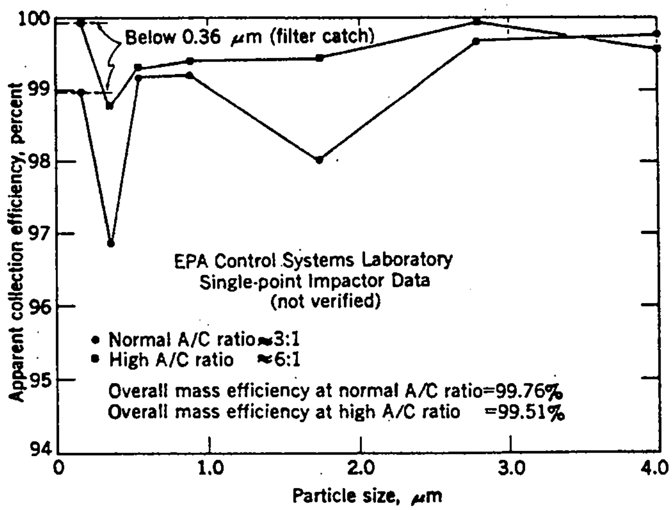


Figure 4.4-8. Baghouse performance, industrial boiler.

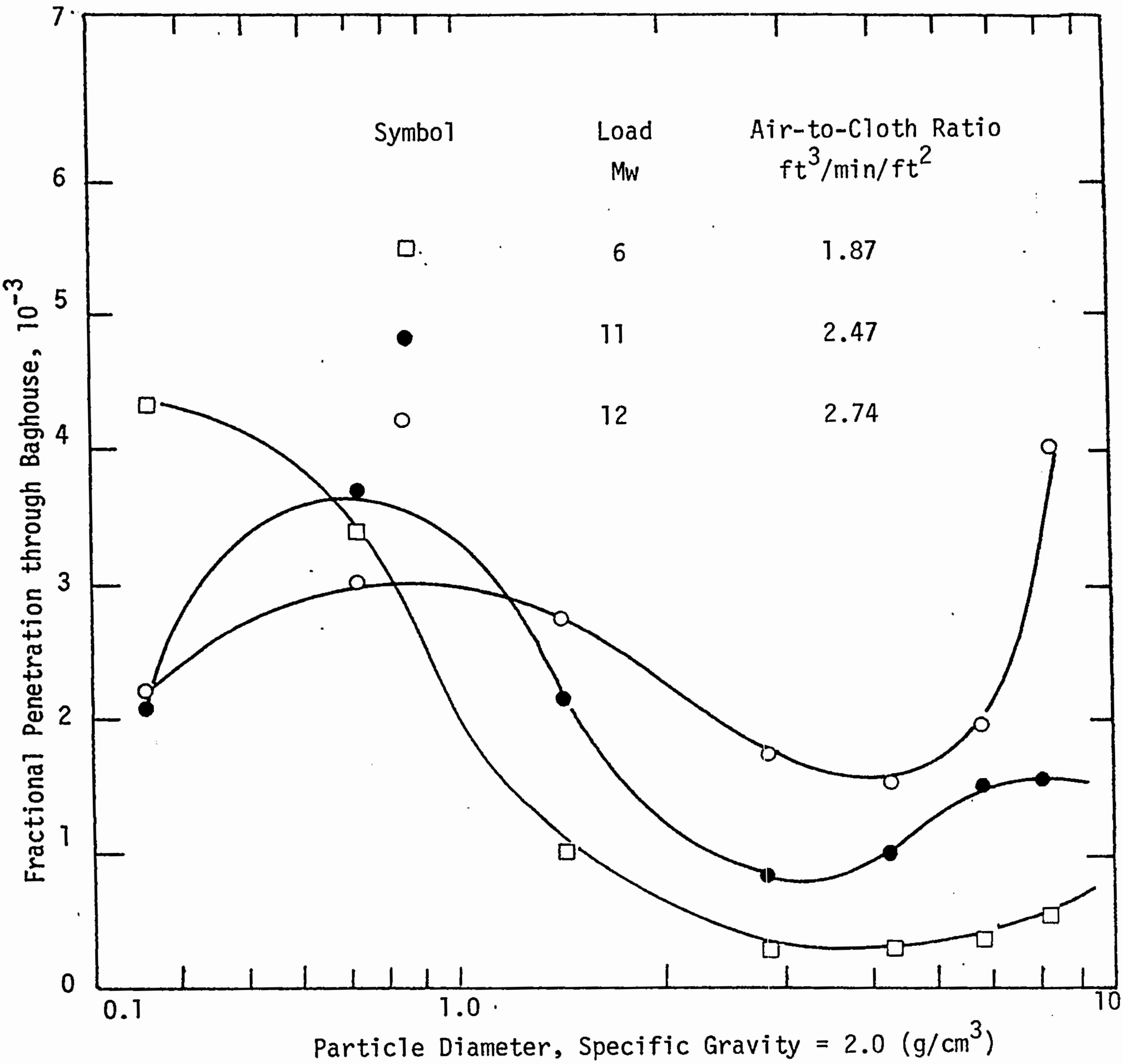


Figure 4.4-9. Fabric filter penetration (adapted from Reference 11).

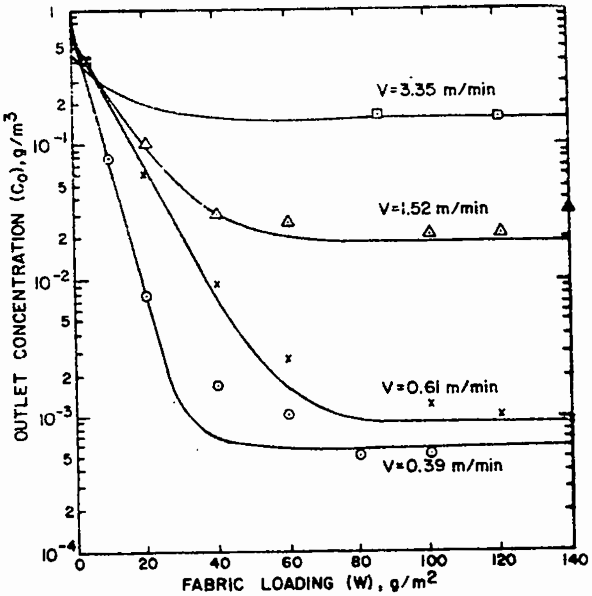


Figure 4.4-10. Effect of air-to-cloth ratio on outlet concentration.

Dennis and Klemm have presented a computerized model useful for predicting performance of shaker-type and reverse-air-type fabric filters. This model is discussed in references 12, 13, and 15.

Penetration through felted bags used in pulse jet fabric filters is believed due to (1) direct passage through the fabric and residual cake (especially following pulse cleaning and (2) seepage of particles through the fabric.[16,17] Particulate emissions can increase substantially at high air-to-cloth ratios.[16,17] Developmental work on models applicable to pulse jet filters are discussed by Dennis, Wilder, and Harmon,[18] and Leith and Ellenbecker.[17]

Emissions from baghouses are not necessarily limited to particle penetration through fabrics. Localized bypassing of filter elements can occur through gaps in sheet welds, around poorly seated seals and gaskets, and through bag tears.[10,19] The outlet particle size distribution would not appear substantially different than that of the inlet although some very large diameter particles may not be able to negotiate a pathway through the narrow gaps.

Theodore and Reynolds have developed the following orifice equation for calculating the increase in penetration due to pinholes, tears, and missing bags.[19]

$$p_c = \frac{0.582}{\phi} (\Delta p)^{0.5} \qquad \text{(Eq. 4.4-1)}$$

where

p_c = increase in penetration.

$$\phi = \frac{Q}{Ld^2 \, (t + 460)^{0.5}} \qquad \text{(Eq. 4.4-2)}$$

where

ϕ = dimensional parameter.

Q = system gas volume, acfm.

L = number of broken bags.

d = diameter of orifice, in.

t = temperature, °F.

ΔP = fabric filter pressure drop, in. H_2O.

For convenience the increase in penetration is plotted against pressure drop and ϕ (Figure 4.4-11). The significance of bag failure can be seen from the following example. If two bags, 6 in. in diameter are removed from a 1415-m^3/min baghouse operating at a static pressure drop of 1.15 kPa, the collection efficiency is reduced by 4.7 percent from 99.5 percent to 94.8 percent. The outlet concentration increases from 4.56×10^{-5} kg/m^3 to 4.72×10^{-4} kg/m^3. Note that the penetration does not depend directly on the total number of bags in the collector or the percentage of the total number failed. The penetration depends only on the absolute number of bags failed. The pressure drop may be reduced as the bag failures increase, and care must be taken to adjust the value if a significant number fail.

4.4.2.2 Pressure Drop. The static pressure drop across the fabric filter is the sum of the static pressure drop across the cleaned fabric and that across the accumulated cake. The latter is a function of time since

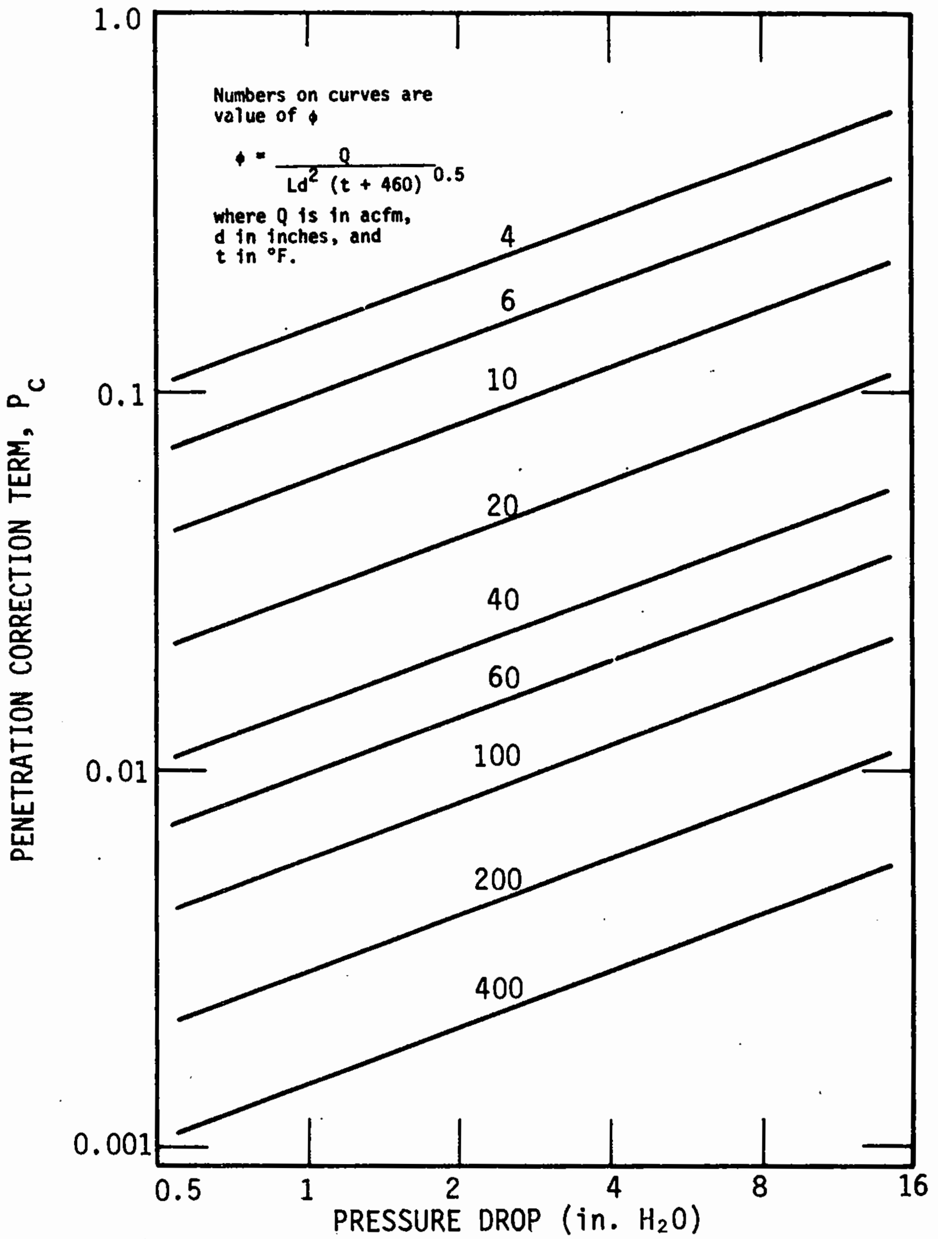


Figure 4.4-11. Penetration correction term as a function of pressure drop and ϕ.

the last cleaning. The curve shown in Figure 4.4-12 represents the uniform deposition of dust of a completely cleaned fabric. The slope of the line is called K_2, the specific resistance coefficient.

The shape of the curve in previously operated systems is not usually like that shown in Figure 4.4-12 since it is difficult to completely clean the fabric. Dennis and Klemm[12,13] have proposed that partial cleaning results in areas where the dust cake has partially "flaked off" and areas where a substantial dust cake remains. This is illustrated in Figure 4.4-13. Using a parallel flow approach, they have modeled gas flow behavior through these different areas. The model has adequately predicted static pressure profiles in laboratory and commercial fabric filter systems.[11,15]

Generally, static pressure drop is proportional to the inlet dust loading, air-to-cloth ratio, fabric structure and cleaning system cycle and intensity. Most units are designed to operate at differential static pressures of 0.5 to 2 kPa, however, some units operate at differential pressures up to 3 kPa.

The static pressure profiles for shaker and reverse air systems tend to have a distinct sawtooth pattern if there are only a few compartments. On larger systems, this pattern disappears and the static pressure drop across the system is relatively constant.[20]

4.4.3 Design of Fabric Filters

A complete characterization of the effluent gas stream is important in the design of a fabric filter system. This would include: gas flow rate, minimum and maximum gas temperatures, acid dew point, moisture content, presence of large particulate matter, presence of sticky particulate matter, particulate mass loading, and presence of potentially explosive gases or particulate. Given accurate data on these effluent characteristics,an appropriate collector can be designed for the required degree of control. Selection of the type of fabric, and dimensions of the bag normally must be done in conjunction with the design of the cleaning system. The size of the fabric filter depends on the air-to-cloth ratio necessary and the number of compartments expected to be out-of-service for maintenance or cleaning at any given time. The overall costs must be balanced against needs for good accessibility and instrumentation, both of which favor improved maintenance and, therefore, improved performance.

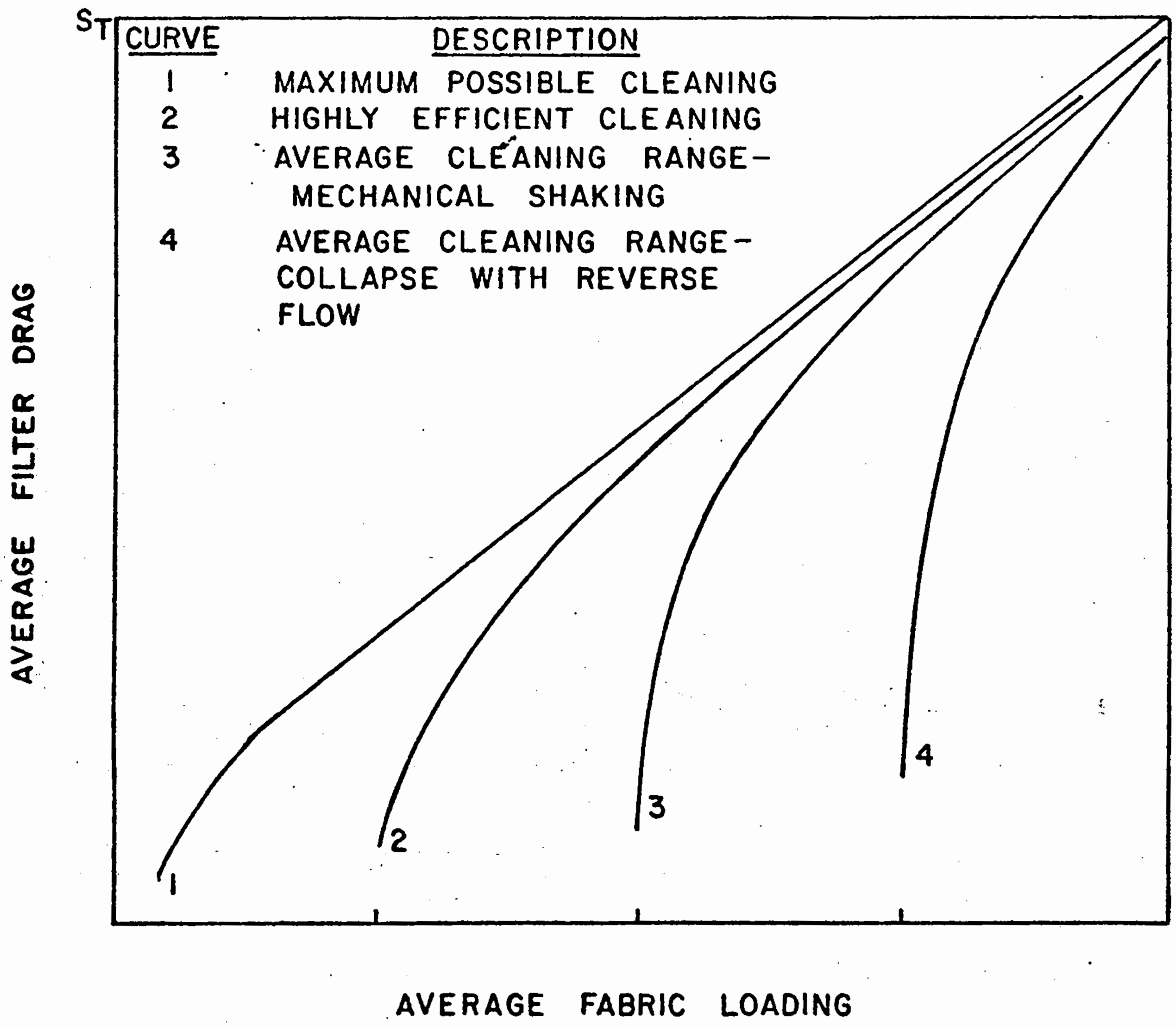


Figure 4.4-12. Filter drag profiles.

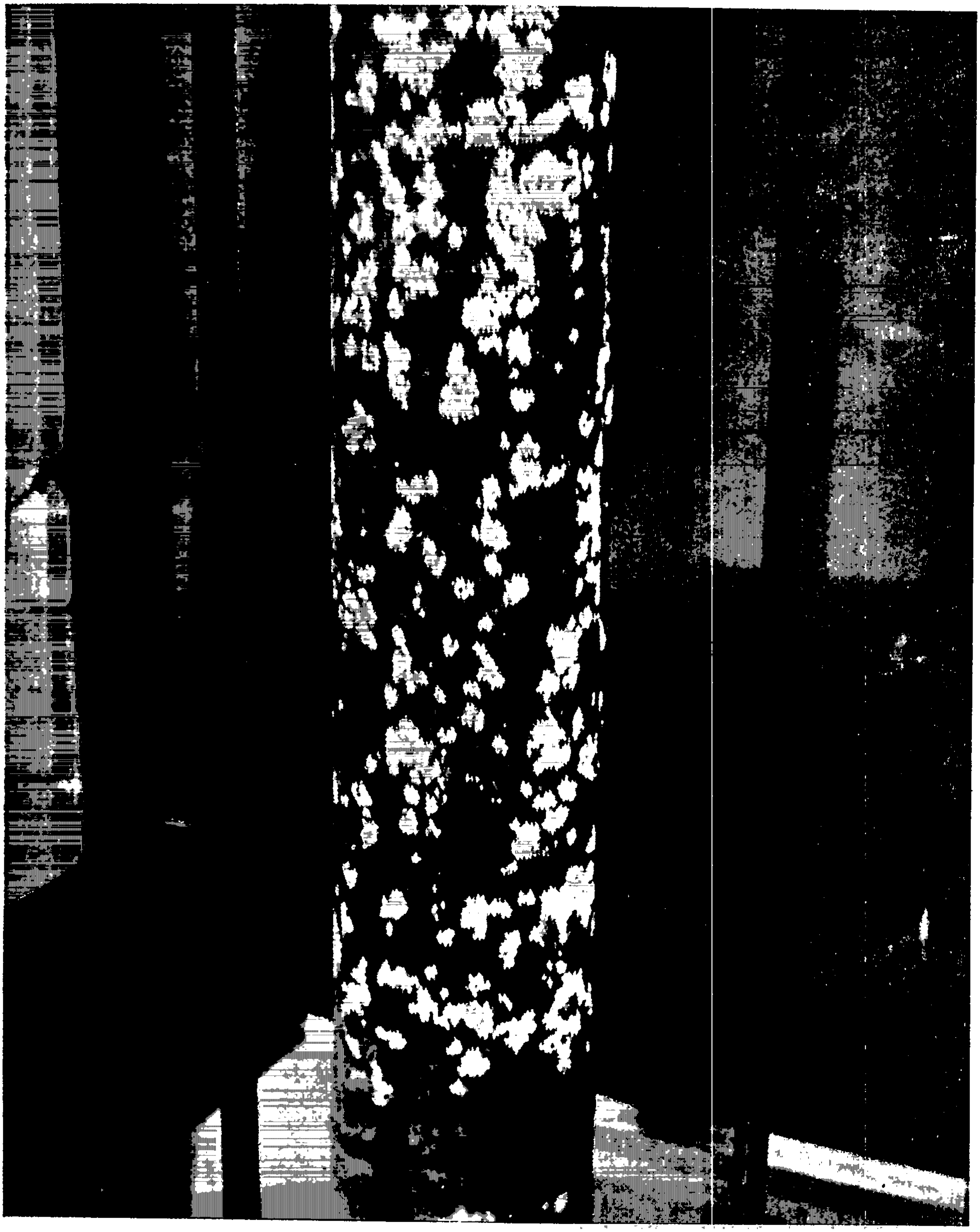


Figure 4.4-13. Fly ash dislodgement from 10 ft × 4 in. woven glass bag (inside illumination).

4.4.3.1 Effluent Characteristics. The effluent characteristics should be quantified to the extent possible before fabric filter design is completed. Variability of these conditions should be considered.

Gas Temperature. The gas stream temperature and its variability over time determine the fiber and finish selected for the filter bag. The temperature of gases emitted from industrial processes may vary over several hundred degrees in short periods of time. Low gas stream temperatures may go below the gas moisture and acid dew points, and high temperatures may exceed the maximum that the fabric will tolerate. The extremes of temperature must be determined before fabric selection.

The temperature of the gas may be modified by using heaters (indirect or direct fired) to increase the gas temperature above the dew point or by using coolers to reduce the gas temperature to one compatible with the fabric. Methods commonly used to increase or maintain gas temperature are insulation of ductwork, use of direct-fired afterburners and heat exchangers, and steam tracing. The use of direct-fired afterburners may serve two purposes: to elevate the gas temperature above the dew point and to remove organics that may blind the fabric surface.

Methods of cooling the gas include dilution, radiative cooling, and evaporative cooling.[2,21] The use of dilution air to moderate gas temperature is the simplest approach, but it may increase the capital cost because the volume of ambient air required may necessitate a substantially larger filter. Figure 4.4-14 shows the increased capacity required when gas temperature is reduced to 560°K by use of 300°K dilution air.

Radiative cooling does not require increased collector size, but it does require an investment in greater duct length. Also, the static pressure drop of the system may be increased by the increased duct length. Figure 4.4-15 shows the reduction in gas temperature achieved as a function of duct length with gases at an initial temperature of 1150°K. Radiation cooling of gases at temperatures above 1150°K requires exotic construction materials and may be uneconomical.[21] The cooling of gases at temperatures below 800°K requires extensive surface area and is usually uneconomical relative to the cost of the greater baghouse capacity required by other cooling methods.[21]

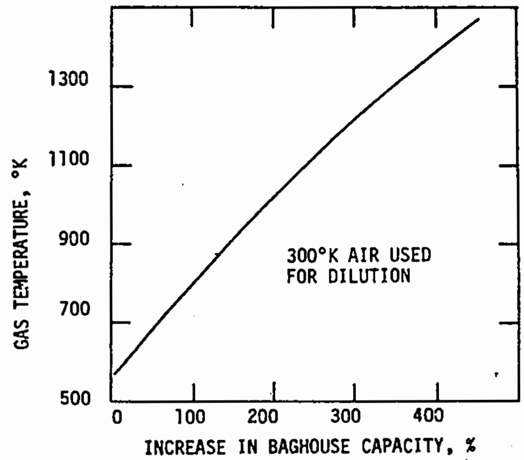


Figure 4.4-14. Added capacity needed in baghouse when hot gases are cooled by dilution with ambient air (reprinted by permission. Vanderhoeck, P., Chemical Engineering, May 1, 1972).

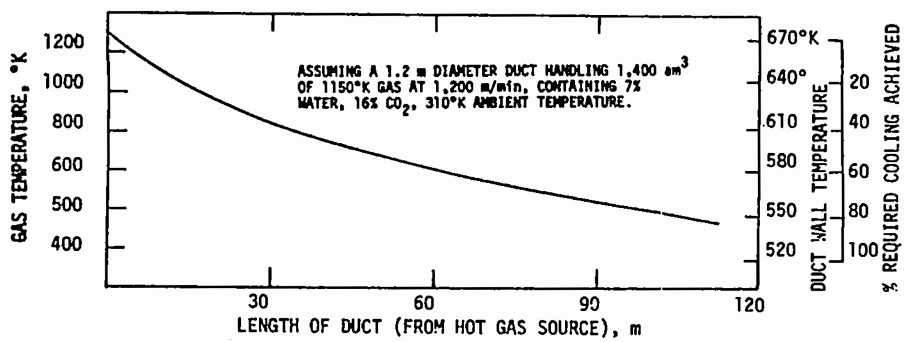


Figure 4.4-15. Radiation effectiveness in cooling hot gases (reprinted by permission; Vanderhoeck, P. Chemical Engineering, May 1, 1972).

Evaporative cooling is accomplished by injection of water into the gas stream. The energy drawn from the gas stream to vaporize the water leads to a reduction in gas temperature. The cooling is accomplished rapidly and in a small space. The system must be designed to reduce gas temperature to a point above the gas dew point, to prevent carryover of unvaporized water droplets into the filter, and to prevent spray water impact on duct walls or liners.[21] Figure 4.4-16 shows the increase in the necessary baghouse capacity as a result of evaporative cooling (desired gas temperature of 560°K). Presently, bags made of graphitized, siliconized fiber glass can withstand this temperature. The water temperature has a relatively minor impact on the quantity of water required.

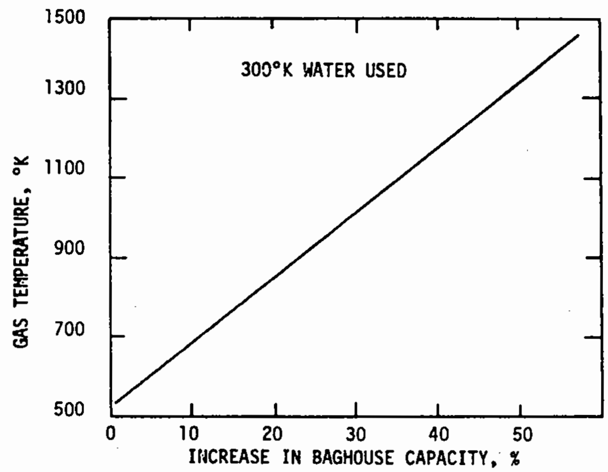


Figure 4.4-16. Added capacity needed in baghouse when hot gases are cooled by evaporating cooling (reprinted by permission: Vanderhoeck, P. Chemical Engineering, May 1, 1972).

Particle characteristics. The particle size distribution of the dust must be considered in design of the collector and in fabric selection. Particle size distribution affects both dust cake porosity and abrasion of the fabric. The presence of fine particles in the gas stream can create a heavy dust cake and increase the static pressure drop through the cake.[22] The small particles can also cause fabric bleeding.

The presence of large abrasive particles can reduce bag life and may require the use of a precleaner or gas distribution devices in the collection system (see the inlet diffuser of Figure 4.4-5). Moreover, because the resistance of the fabric to abrasion is greatly reduced when particles strike tangentially, the presence of large particles may require modification of gas inlet design. For certain sources such as spreader stoker boilers, a mechanical collector ahead of the fabric filter may provide protection from the large quantity of >10 μmA particles. This would also allow protection from glowing embers and thus reduce the risk of hopper fires.[23]

Particulate matter with a high carbon content may be generated during periods of improper combustion. Fabric filter design should include ways to minimize hopper fires.[24,25] These could include continuous removal of collected material, limited air entry into hoppers, and a fire-sensing system.[20,24]

Sticky particulate can be difficult to remove from the fabric surface. A survey done by Billings and Wilder indicated blinding of bags due at least partially to sticky particulate was the most frequent problem reported.[26] Improper combustion can lead to problems of this type and result in substantially increased static pressure drop.[27]

Gas Composition - Factors of importance regarding the gas composition include moisture content and acid dew point. If a fabric filter is operated at close to the acid dew point, there is a substantial risk of corrosion especially in localized spots close to hatches, in dead air pockets, in hoppers, or adjacent to heat sinks such as external supports.[28,29] If the operating temperature drops below the water dew point, either during start-up or at normal operation, blinding of the bags can occur. The presence of trace components, such as fluorine, can attack certain fabrics.

4.4.3.2 Fabric Selection. Fabric selection is usually based on the prior experience in similar applications. Important factors to consider are:

Dust penetration
Continuous and maximum operating temperatures
Chemical degradation
Abrasion resistance
Cake release
Pressure drop
Cost
Cleaning method
Fabric construction.

The choice of fabric ultimately affects pressure drop, selection of cleaning method, outlet concentration, and the life of the fabric under operating conditions.

Temperature. Degradation of the polymer in synthetic and natural fabrics is accelerated temperature. The rate of decay is also enhanced by the actions of moisture, chemicals, and abrasive particles. Temperatures at which reasonable performance can be expected under normal conditions are given in Table 4.4-1, which gives the continuous maximum operating temperatures recommended by fabric manufacturers and summarized by Theodore and Buonicore.[2]

The maximum short-term temperature represents the temperature at which rapid deterioration will result in immediate failure. For synthetics, this is the temperature at which polymer softening occurs and causes permanent elongation. Figure 4.4-17 shows the reduction in strength of Nomex® fabric with increasing temperature.[30]

Glass fabrics are sensitive to abrasion between fibers and are normally coated with either Teflon® or silicon-graphite. Polymer finishes can degrade with increasing temperature. Figure 4.4-18 shows the effect of gas temperature on the finish of glass fiber bags.[31]

Chemical degradation. Chemical degrading of the fabric is caused by the breaking of polymer chains within the fiber structure. The degrading may be from acid hydrolysis, alkali attack, or, in the case of glass fiber fabrics, conversion of the structure to a noncrystalline form that has lower strength.

As the chain length of a polymer is reduced by chemical attack, it loses strength. The chemical attack may be accelerated by moisture or metal catalysts in the dust impregnated in the fibers. The rate of attack increases with temperature.

Chemical composition of the gas stream, moisture content, and temperature must be considered in selection of the fabric. Table 4.4-2 indicates the ratings of commercial fabrics with respect to chemical resistance. Note that resistance is a relative term that does not imply total resistance to a specific chemical. Also resistance may be greatly reduced by cyclic operation under different conditions and concentrations.

Abrasion resistance. Resistance to abrasion is a relative term that indicates the ability of a fabric to provide extended service in collecting abrasive dust. Resistance can be modified by fabric construction, fabric finish, and shapes of the particles collected.

Table 4.4-1. RECOMMENDED TEMPERATURE LIMITS FOR VARIOUS COMMERCIAL FABRICS[2]

Fabric	Generic name	Type yarn	Maximum temperature range, °K		Melting temperature, °K
			Long periods of time	Short periods of time	
Cotton	Natural fiber cellulose	Staple	350	380	420 decomposes
Wool	Natural fiber protein	Staple	370	400	575 chars
Nylon®	Nylon polyamide	Filament spun	370	400	520
Dynel®	Modacrylic	Filament spun	350	390	440 softens
Polypropylene	Polyolefin	Filament spun	370	400	440
Orlon®	Acrylic	Spun	390	410	520 softens
Dacron®	Polyester	Filament spun	410	440	420
Nomex®	Nylon aromatic	Filament spun	490	530	640 decomposes
Teflon®	Fluorocarbon	Filament spun	500	530	670 decomposes
Fiberglass	Glass	Filament spun bulked	530	590	1070
Stainless steel (type 304)			1000	No data	1700

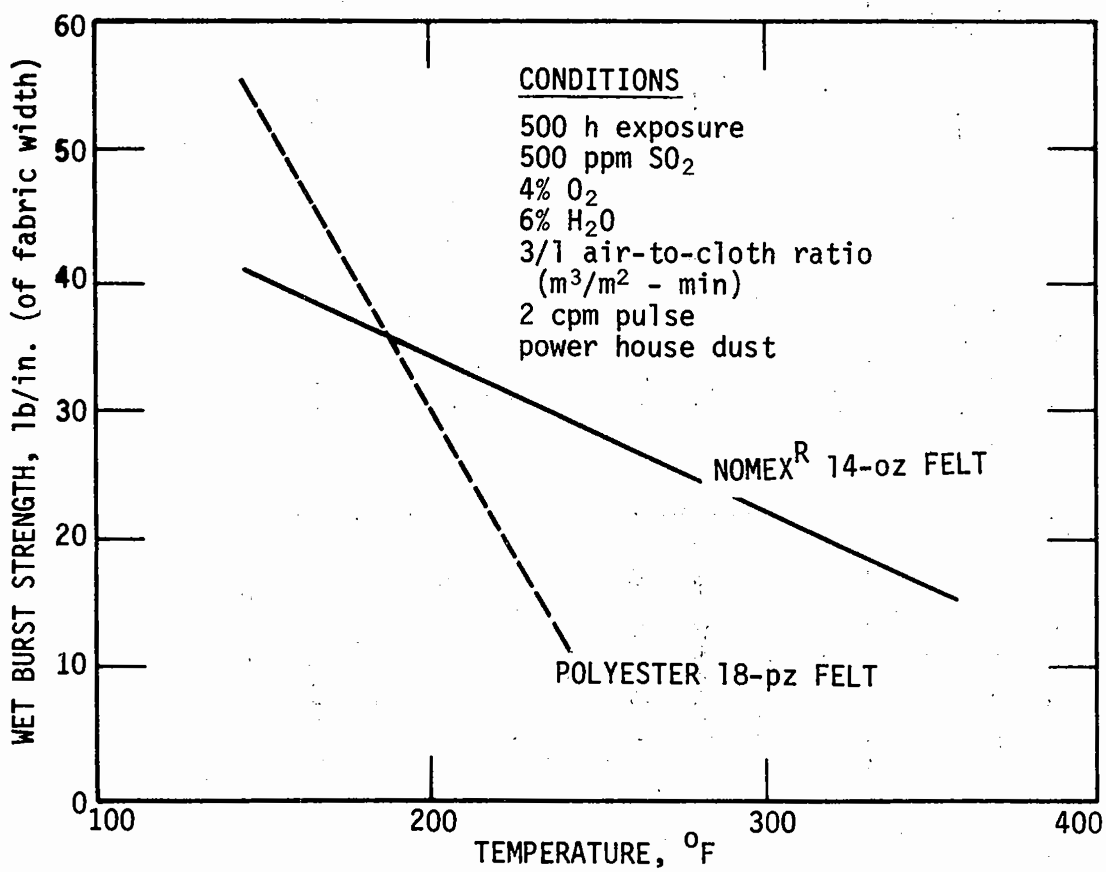


Figure 4.4-17. Effect of acid and temperature on strength of Nomex[R] and polyester fabrics (reprinted by permission: E. I. du Pont de Nemours and Company).

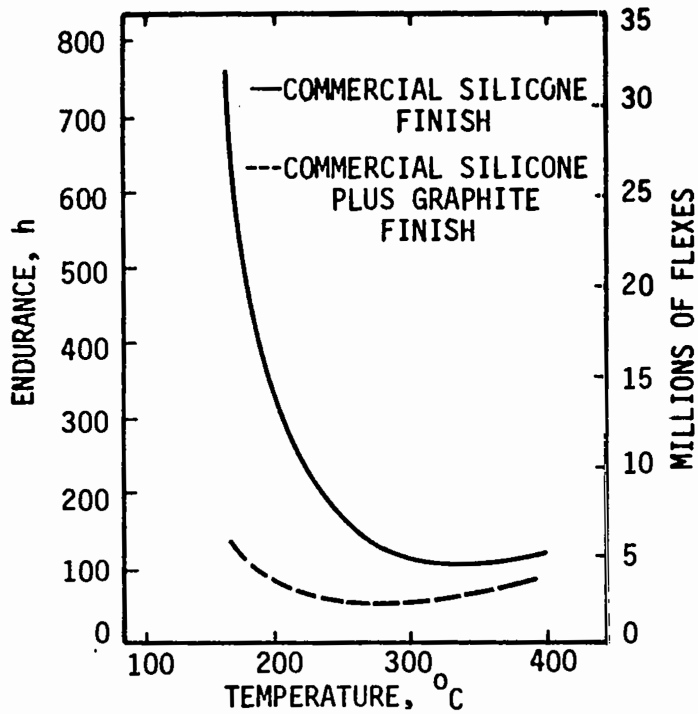


Figure 4.4-18. Effect of gas temperature (continuous) on life of glass fabric bags (reprinted by permission: Menardi and Company).

Table 4.4-2. CHEMICAL RESISTANCE OF COMMON COMMERCIAL FABRICS[2]

Fabric	Generic name	Type yarn	Acid resistance	Fluoride resistance	Alkali resistance	Flex and abrasion resistance
Cotton	Natural fiber cellulose	Staple	Poor	Poor	Fair-good	Fair-good
Wool	Natural fiber protein	Staple	Very good	Poor-fair	Poor-fair	Fair
Nylon	Nylon polyamide	Filament spun	Fair	Poor	Very good-excellent	Very good-excellent
Dynel®	Modacrylic	Filament spun	Good-very good	Poor	Good-very good	Fair-good
Polypropylene	Polyolefin	Filament spun	Excellent	Poor	Excellent	Very good-excellent
Orlon®	Acrylic	Spun	Good-excellent	Poor-fair	Fair	Fair
Dacron®	Polyester	Filament spun	Good	Poor-fair	Fair-good	Very good
Nomex®	Nylon aromatic	Filament spun	Fair	Good	Excellent	Very good-excellent
Teflon®	Fluorocarbon	Filament spun	Excellent	Poor-fair	Excellent	Fair
Fiberglass	Glass	Filament spun bulked	Fair-good	Poor	Fair	Poor
Polyethylene	Polyolefin	Filament spun	Very good-excellent	Poor-fair	Very good-excellent	Good
Stainless steel (type 304)			Excellent		Excellent	

Pressure drop. Static pressure drop must be considered in selection of the fabric. The residual pressure drop affects the cost of operation due to an increase in fan horsepower. In applications where the fan capacity is limited, the increase in pressure drop can reduce gas volume and reduce capture and transport velocity in the ventilation system.

Cleaning method. The method of removing the dust cake is closely related to fabric construction and fiber type. With woven fabrics that are subject to abrasion or flex damage, gentle cleaning methods such as low-frequency shaking or reverse air can be used. With felted fabrics, a more intense cleaning method is required, such as high-pressure reverse air or pulse-jet cleaning. An improper combination of fabric and cleaning method (e.g., intense shaking of glass bags) can cause premature failure of the fabric, incomplete cleaning, or blinding of the fabric (complete plugging of pores).

Fabric construction. Filter fabrics commonly used in operating facilities are either woven or felted. Unlike woven fabric, felt is a genuine filter medium and is more efficient in collection of particulate at comparable filtering velocities; it is, however, more expensive. Felted fabrics are composed of randomly oriented fibers and are relatively thick. Needling the fibers meshes them and forms a strongly bonded fabric. The thickness of felt provides for maximum particle impingement, but increases the static pressure drop (reduces permeability). Felted fabrics are normally used in pulse-type units and are operated at high A/C ratios.

Woven fabrics are characteristically used in shaker and reverse-air filters, and are operated at relatively low A/C ratios. Woven fabric is made up of filament or staple (spun) yarns in a variety of patterns, having various spacings between the yarns, with a specific finish that is designed to retain or shed filter cake, depending on the application. Seven of the most common weave patterns are shown in Figure 4.4-19. Plain weave is lowest in initial cost, and has the least porosity and greatest particle retention; however, its potential for blinding is greatest. Twill weave has medium retention and blinding characteristics and has reasonable permeability. Twill weave also exhibits the best resistance to abrasion. Sateen weave has the lowest particle retention, is easiest to clean of accumulated dust, and has lowest potential for blinding.

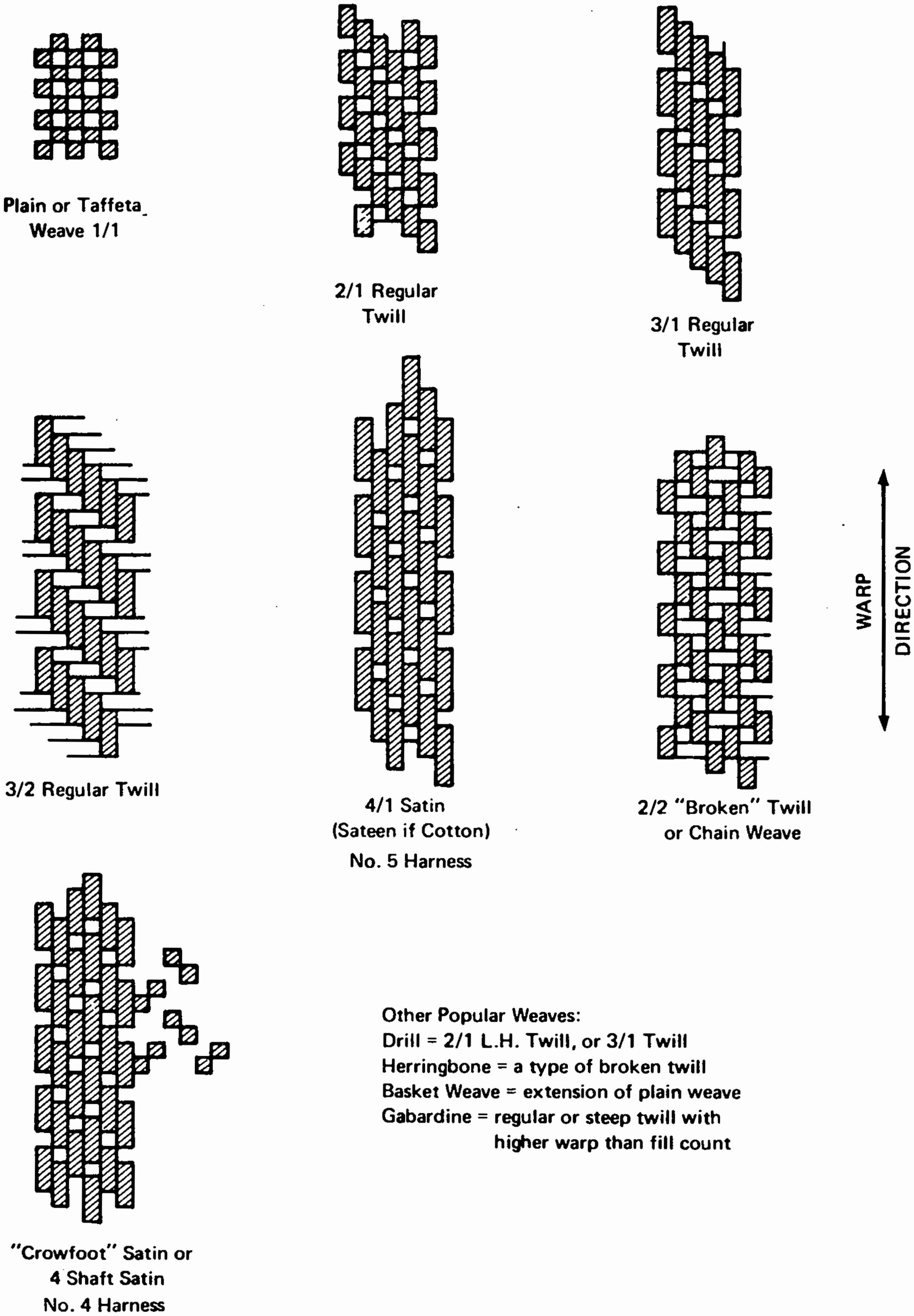


Figure 4.4-19. Typical fabric weaves (reprinted by permission: Industrial Gas Cleaning Institute).

The permeability of woven fabrics depends on the type of fiber, tightness of twist, size of yarn, type of weave (geometric pattern), tightness of weave (thread count), and type of fabric finish.

Woven fabrics may be provided with a number of finishes. Cotton fabrics may be preshrunk to maintain dimensional stability, i.e., resistance to stretching or shrinking in any direction, which could adversely affect other fabric characteristics. Spun fiber fabrics may be napped on the surface receiving the dust load. Napping is the process of pulling fibers out of the yarn bundles to form a soft pile; this promotes the formation on the fabric surface of a dust cake that does not penetrate the interstices of the fabric. Synthetic fabrics may be heat-set to ensure dimensional stability and provide a smooth surface with uniform permeability. Any fabric may be silicone treated (also used in combination with graphite and Teflon®) to improve abrasion resistance, to facilitate cake release, and to reduce moisture absorption.

4.4.3.3 Selection of Cleaning Technique. A number of factors are considered in the selection of a cleaning technique for a fabric filter system. Primarily, the physical and chemical properties of the flue gas and particulate must be clearly defined. Specific case studies involving similar processes, together with laboratory studies, are often the most informative guideposts for design parameters. Critical interdependencies in cleaning technique selection are particulate characteristics/cleaning method, specific resistance/cleaning method, and cleaning method/service life. Constraints imposed by intermittent or continuous operation and by availability of space must also be considered.

If the dust cake is released readily from the fabric, reverse air cleaning may be adequate. Reverse air can be used in combination with mechanical shaking. Felted fabrics generally are not cleaned by reverse air because of their greater structural depth and, hence, greater dust retentivity. Bag tensioning and reduction of reverse air flow rates minimize the degree of bag flexure and thus reduce the risk of accelerated bag wear. These measures also prevent complete collapse of the bag, which makes cake removal difficult. The rate of flexure is probably the controlling factor with respect to fabric failure.

Reverse-air and mechanical-shake units are capable of being cleaned only while the unit or a single compartment is off line. In most combination reverse-air and mechanical-shake systems, bag collapse and/or flexure caused by flow reversal are the major dust dislodging forces.

In shaker systems, the fabric cleaning action is defined by quantifying shaking frequency, shaking amplitude, and duration of the shaking interval. Tensioning of the bags is important in determining average amplitude and acceleration of the bag. If the bag is too slack, the transmission of cleaning energy over the entire length of the bag is incomplete, with the result that cleaning is inefficient and nonuniform. This can lead to abrasion damage and reduced bag life.

4.4.3.4 Sizing. The size of a fabric filter system is determined by the gas volume to be filtered and the A/C ratio at which the filter can be operated in view of fabric type, dust cake properties, and cleaning method. The area of fabric surface is determined by multiplying the total gas flow by the recommended A/C ratio.

Penetration is directly related to the effective air-to-cloth ratio in the system, with substantially increased emission levels at high air-to-cloth ratios.[13,14,34] Accordingly, the lowest possible face velocity consistent with economic constraints should be specified.

The minimum number of compartments in shaker-type and reverse-air units is related to the maximum allowable increase in A/C ratio as one or more compartments are removed from service. The following additional factors should be considered for compartmentalization in fabric filter design:

1. Large compartments may necessitate oversized and uneconomical cleaning equipment.

2. Large compartments contain more bags and, therefore, present a higher probability that bag failure will occur in a single compartment. This eventuality could necessitate intermittent replacement of bags.

3. Large compartments require large ducts and dampers; small compartments require more numerous, but smaller, ductwork branches and dampers.

4. Large compartments require larger solids-collection hoppers.

5. Larger compartments cool more slowly when brought off line for maintenance.

Most of these considerations favor smaller, more numerous compartments.

The compartments of shaker and reverse air should be arranged so that maintenance of all filter tubes is relatively simple. The number of rows of bags along each walkway should be minimized so that the bags nearest the compartment walls can be reached without disturbing too many bags near the walkway. The appropriate "bag reach" is determined by the layout of tubes and the diameter. Normally there are no more than 3 to 4 bags deep.[35,36]

4.4.3.5 Solids Removal Equipment. As solids are cleaned from the filtering fabric, they fall to a collection hopper for ultimate removal. The "fluid" properties of the collected solids are important in design and operation of these systems, and they may be markedly different from the properties of the material from which they originated. Fine dusts, for example, tend to pack more readily than coarser materials; moreover, condensation formed in the filter device may cause solid material to agglomerate. Both of these factors can make solids disposal difficult.

Various design features can help prevent the clogging of solids collection hoppers. The hopper should be designed with a steep valley angle; angles of 55 to 70 degrees are recommended. Hoppers should also include large discharge openings, smooth coatings (i.e., epoxy or Teflon^{R}) on inside surfaces, and minimal ledges or other obstructions on sidewalls. The top of the hopper sidewall should drop vertically and begin the slope to the discharge point at least one bag diameter below the bottom of the bags to allow proper dust discharge. At least 0.3 m of clearance should be provided between hopper walls and any internal partitions to allow easy discharge.

Heaters and insulation can be installed in hoppers to prevent condensation and caking of collected material. Jets of hot air can be used to fluidize material in the hopper and keep it free flowing.

Solids are generally removed from the hopper by means of a discharge valve, which removes ash from the hopper while preserving the pressure differential between the dust conveyance system and the fabric filter system.

The solids are transported to a collection point by means of screw conveyors, pneumatic (either vacuum or positive systems) systems, and wet sluicing systems. Screw conveyors, which are common on small systems, work well in a variety of applications but are sometimes cumbersome.

Pneumatic systems are not limited to straight-line runs as are screw conveyors, and, therefore, are more flexible. Particularly abrasive solids must be accounted for in the design of pneumatic systems by appropriate materials of construction and in some applications by installation of replaceable wear plates at turns. Sluice systems are normally found in coal-fired boiler applications for transport of the boiler bottom ash.

4.4.3.6 Instrumentation. Reliable operation of a fabric filter is favored by the use of the following instrumentation:

1. Thermocouples or other temperature-measuring instruments located at the device inlet.

2. Inlet/outlet differential static pressure gages.

3. A single-pass transmissometer (opacity meter).

4. Compressed air pressure gage.

5. Fan motor ammeter.

In lieu of differential pressure gages, it is sometimes simpler to install static pressure taps where appropriate and use a portable meter to obtain readings. This approach reduces problems of meter moisture damage, meter corrosion, and plugging of lines. Where permanent differential static pressure gages are used, the static pressure lines should be as short as possible and free of 90-degree elbows. Copper tubing has been found to be less susceptible to deterioration than the polypropylene lines commonly used.

Recording temperature meters are especially useful in identifying high or low-temperature excursions, which rapidly destroy fabrics. As a less expensive alternative, high-temperature indicators composed of colored fiber or temperature-sensitive plugs may be used.

The single pass transmissometer may not provide an accurate measurement of effluent opacity; however, it is useful in identifying problems. A significant leak is detected in a specific compartment by a drop in the opacity when that compartment is off-line for maintenance.[20]

The instrument readouts are best mounted on a master control panel as close as possible to other process monitoring displays. The readings of thermocouples, pressure differential gages, and transmissometers can all be electronically recorded for permanent records.

4.4.3.7 Fire and Explosion Protection. Provision should be incorporated into the fabric filter design to protect personnel and equipment in the event of an explosion. Such events can occur even in units supposedly collecting inert particulate matter.[24,25]

One common means to minimize damage is to install explosion vents to release generated gases at the onset of an explosion. The two basic types of vents are the diaphragms and the free-hanging door. Information concerning the sizing and location of explosion vents is presented in references 37 and 38.

4.4.3.8 Other Factors. Several potential operating problems can be minimized by means of proper design.

In the case of pulse jet filters, water and oil in the compressed air lines can be deposited on the interior bag surfaces. Resultant blinding can be minimized by using driers on the compressers and drains on the bottom of the supply manifold. The blow tubes should be firmly secured at the far end so that the shock does not shear the retaining pin and allow the blow tube to wander.

Abrasion at the bottom of bags in reverse-air and shaker-type collectors can be reduced by design of a good thimble arrangement. The thimbles should be at least one bag diameter long to prevent abrasion caused by particulate "turning the corner" at the cell plate and being thrown to the outside by inertial force.[23,24] The thimbles act as flow straighteners and protect the bottom of the bag from excessive abrasion. A properly designed unit is shown in Figure 4.4-20. Note the rounded edge on the top of the thimble to reduce cutting of the fabric even if tension is not optimum. For units in which the base snaps into the tube sheet, a thimble can be added which extends downward to provide the same type of abrasion protection as that shown in the illustration.

A bypass may be advisable, especially when process startup or upset conditions could generate sticky particulate or result in gas temperatures

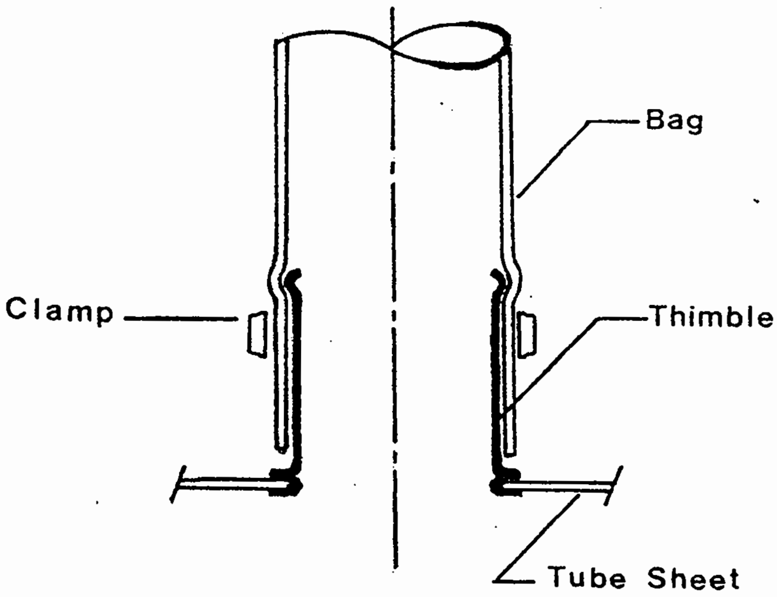


Figure 4.4-20. Cross section of a thimble protecting bottom of bag (reprinted by permission: Mr. E. W. Stanly).

below the acid vapor or water dew points. These could also be used in conjunction with a spark sensor to reduce risk of fire.

Inlet and outlet dampers should be provided in compartmented systems to allow on-line maintenance. The dampers must be designed to provide positive sealing so as to protect maintenance personnel from toxic gases.

The reverse-air fan provides cleaning of the bags by reversing the system gas flow. The fan must be designed to deliver the necessary gas volume at a pressure drop greater than the resistance of the filter.

Welds around tube sheets, thimbles and hoppers should be continuous. Tack welding leaves gaps through which a relatively large quantity of gas can pass untreated. The crevices created by task welds also provide sites for corrosion.

Access doors should be large enough that maintenance personnel can conveniently enter while wearing safety equipment such as self-contained rebreathers. These should be secured by several firm, yet easy-to-remove latches. The use of a large number of bolts discourages routine access, which is necessary at most installations. A chain should be available adjacent to the door to secure the door during periods when personnel are inside. The chain provides additional security beyond that of the lock-out system.

Additional information regarding fabric filter design is references 1, 2, 35, 40, 41, and 42. Models are available to predict the operations characteristics of reverse-air and shaker-type fabric filters.[12,13,15]

4.4.4 Operation and Maintenance of Fabric Filters

The long-term satisfactory performance of fabric filters is at least partially dependent on proper operating procedures and a preventive maintenance program.

4.4.4.1 Startup/shutdown. A fabric filter is especially vulnerable to corrosive vapors and sticky particulate during startup and shutdown. In some cases, it may be advisable to bypass the collector until the effluent gas stream temperature is above the acid dew point temperature.[39]

Prior to startup, a precoat of the material to be collected can be placed on the bags by the injection of suitable material into the inlet duct. This precoat is valuable for new fabrics in that it aids in the conditioning of the fabric. Exposure of the new fabric without the precoat could lead to deposition of fine particles within the fabric itself or the collection of hard-to-remove sticky material on the fabric surface.[20,23] Typically, a material similar to that to be collected is used as a precoat; however, prudence should be applied because of potential problems. Use of materials such as lime, for instance, has resulted in blinding problems because of the hygroscopic nature of lime which lead to the formation of a lime mud on the fabric surface.[39]

4.4.4.2 Fabric tension. The adjustment of bag tension is important in ensuring adequate bag life and minimum particulate emissions.[33,39,40,43] The bag should be tight enough to avoid excessive fiber-to-fiber and bag-to-bag abrasion, but not so tight as to exceed the tensile strength of the bag during cleaning. It may be necessary to check bag tension soon after startup.[39]

4.4.4.3 Cleaning system. Operation of the cleaning system should be evaluated regularly. Cleaning intensity and frequency can have a direct and substantial impact on both bag life and emissions. For example, Dennis and Wilder[44] found in one installation that penetration from a shaker-type unit was related to the shaker amplitude. Ladd, et al.[33] reported that adjustment of shaker frequency contributed to a reduced rate of bag failure. The gas flow rate and static pressure available in a reverse air fan can also be an important operating variable.[27]

4.4.4.4 Solids removal. Accumulation of solids within the hopper can lead to major operational problems. A partially filled hopper can lead to particulate matter reentrainment and abrasion of the lower portions of the bags.[25] The material in the hopper can gradually cool and bridge over. Ultimately, bridging could lead to a restriction of gas flow to the bags and to a buildup of material into the bags. Collected material with a substantial combustible content can be prone to fires.

On a frequent basis, operators should confirm positively that solids are being discharged. For units with rotary valves, the use of a long (0.5 m), brightly colored rod attached to the end of the shaft has proved useful in determining from a distance that a rotary valve has stopped. Motion sensors can be used on rotary valves and screw conveyors.

4.4.4.5 Fabric and Component Repair. When bag failure is the result of localized abrasion or mechanical damage, small pinholes or tears are usually sealed by adhesive and sewn with thread. The adhesive and thread should be compatible with the original fabric in the properties of shrinkage, temperature tolerance, and chemical resistance. Successful repair depends on the strength and condition of the bag. Patching may not be successful on bags that have been operated for a long period and have undergone chemical and thermal degradation. Bag repair must be considered relative to the cost of bag replacement. Repair becomes economically attractive when bags are extremely large (>30-cm diameter) or when the fabric is expensive.

The blinding of bags because of process upset, operation below dew point, or moisture inleakage can increase filter pressure drop. If the bags are new and have not been subjected to chemical or thermal degradation, it is possible to reduce the fabric resistance by laundering. Although it is not available for all fabric types, laundering can sometimes make it possible to put off bag replacement until a later date. Care must be taken to prevent bag shrinkage or chemical attack during cleaning. Even though the expected bag life may even be reduced, the overall cost may be lower than that incurred by total bag replacement or operation at higher static pressure.

Reuse of bags and cages after a fire in a baghouse is usually not possible and almost never advisable. High temperatures can warp the cages to the extent that bag-to-bag abrasion results. Cages may be reused only if they are not corroded or bent. Each cage must be carefully inspected before installation.

4.4.4.6 Maintenance Inspection. Regular inspection of the inside of bags is necessary to confirm that the system is in compliance with regulatory requirements and that there are no developing problems. Safety procedures must be strictly followed. Diagnosis of prevailing operation is done primarily by observation of "clean" side deposits resulting from penetration of dust. If the penetration is local to specific bags or seals, the pattern created by the dust on the tube sheet may indicate the point of penetration. Figure 4.4-21 shows the characteristic pattern of a low velocity dust penetration at the snap-ring attachment in a shaker baghouse. The small depressions that look like craters are the penetration points. In the early stages of penetration the pattern can also be highlighted with a fluorescent dye and an ultraviolet light source. The use of fluorescent dyes is not practical where total failure of a bag has occurred or the problem has existed for an extended period.

Moderate clean-side deposits may be caused by a single small pinhole in a bag. Again, the pattern of dust generated by penetrating gas flow can indicate the location of holes. Figure 4.4-22 shows the dust pattern indicated by the clean area on the tube sheet as a result of the gas impingement. Impaction of the particles on bags on the opposite side of the collector is indicated by the discoloration. The abrasion caused by this high-velocity jet results in cascading bag failures in the collector.

Abrasion can occur if an adequately designed precleaner or baffle plate is not used to remove large, abrasive particles. Figure 4.4-23 shows the abrasive damage caused by large, sharp particles impinging on the bag surface

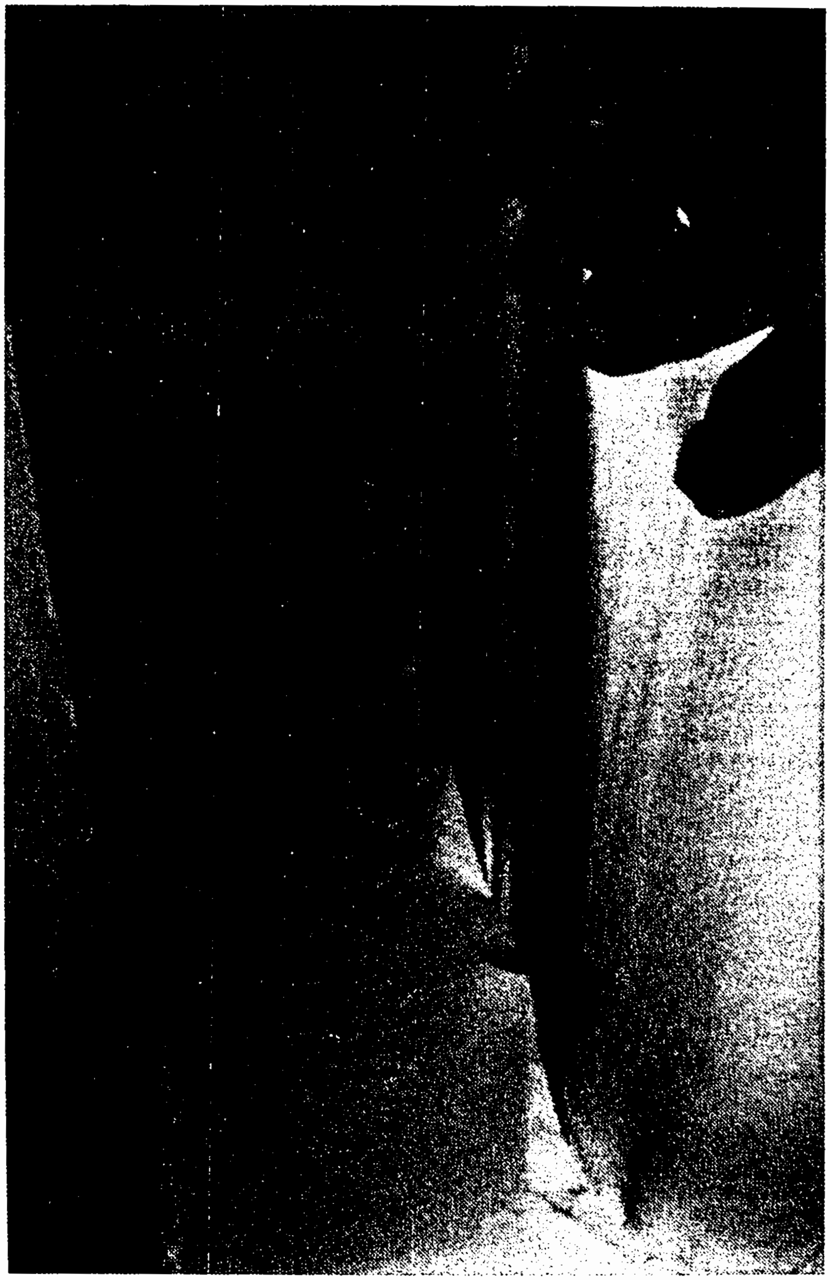


Figure 4.4-21. Dust penetration around snap-rin attachment.
(Courtesy of PEDCo Environmental, Inc.)

Figure 4.4-22. Gas jet adjacent to pin hole. (Courtesy of PEDCo Environmental, Inc.)

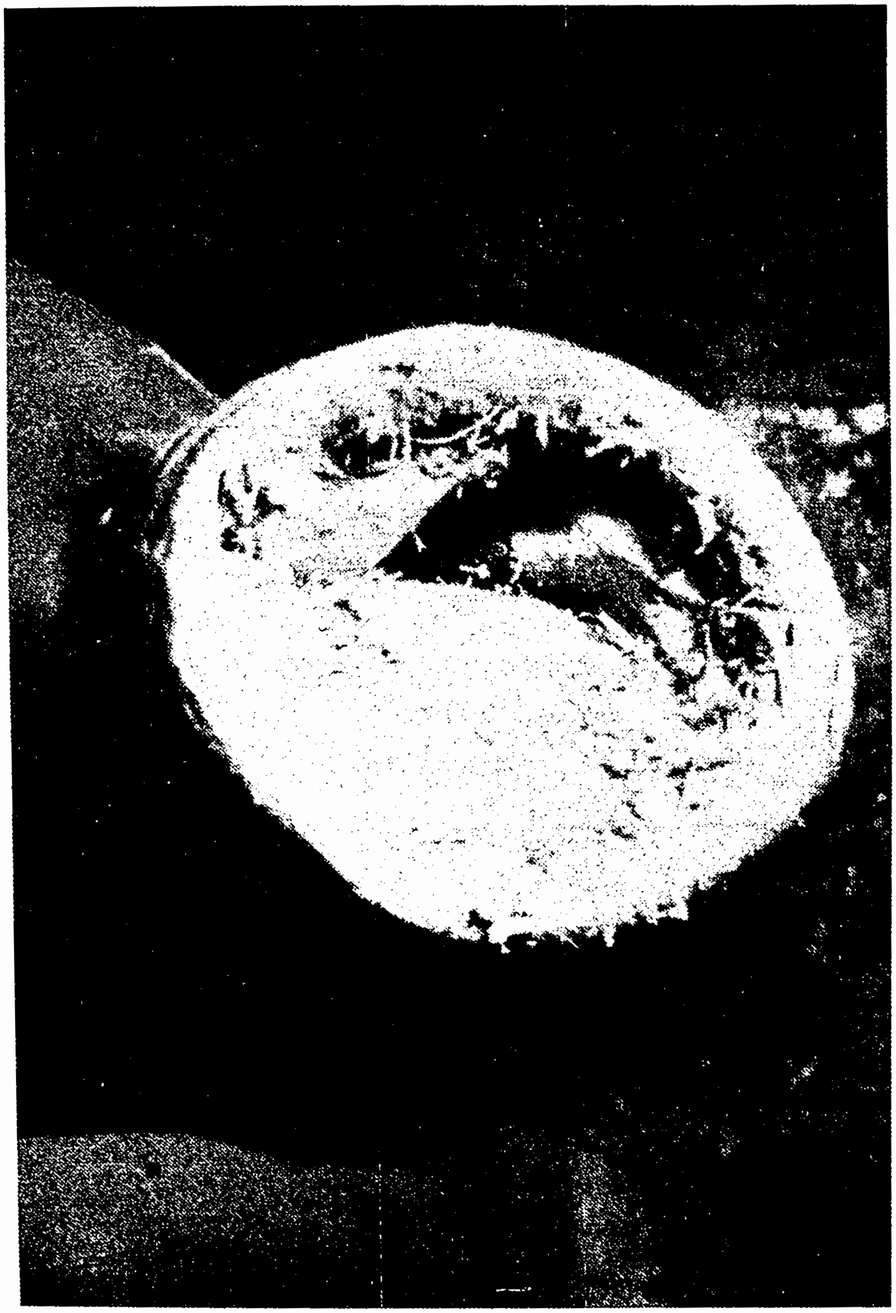


Figure 4.4-23. Abrasion damage at bag inlet. (Courtesy of PEDCo Environmental, Inc.)

near the bag cuff. In this design the installation of thimble extensions, blast plate, or precleaner would reduce the abrasive damage and extend bag life. Most abrasion problems occur near the bottom of the bags directly above the thimbles. Hopper overflow can also be detected at the bottom of bags, especially in bags located in corners or along the outer walls of the compartment.

4.4.4.7 Cleaning System Operation. The cleaning system (shaker, reverse air, pulse jet) should be checked for proper operation. When the cleaning system malfunctions, an accompanying increase in filter static pressure drop is usually noted. The motor and cam arrangement should be inspected for wear and linkage failure. The dampers and fans of reverse-air systems should be checked for correct operation. The pulsing of individual solenoid/diaphragm systems on pulse-jet cleaning mechanisms should be checked. The compressed air pressure should be checked, and proper operation of compressed air dryers should be verified.

During operation, the stack opacity should be checked regularly. A spike in visible emissions can often be related to the pulse cleaning of a specific row of bags, thus aiding in the eventual identification of the bag or bags causing the problem. On compartment type reverse-air or shaker units, a reduction in opacity during cleaning of a specific compartment is indicative of a problem in that compartment.

4.4.4.8 Preventive Maintenance. A preventive maintenance program should be aimed at reducing bag failure. The program should include routine servicing of mechanical equipment including gears, bearings, and pneumatic cylinders and also should include a complete external and internal inspection of the system at frequent regularly scheduled predetermined intervals.

The operator should maintain records indicating system pressure drop, temperature, date of bag replacement and location of the bags, and changes in process operation. These data may then be used to diagnose failure mechanisms and provide direction in preventing recurrence of failures.

An example of the types of records useful in diagnosing recurring problems is shown in Figure 4.4-24. The top figure reflects a random type

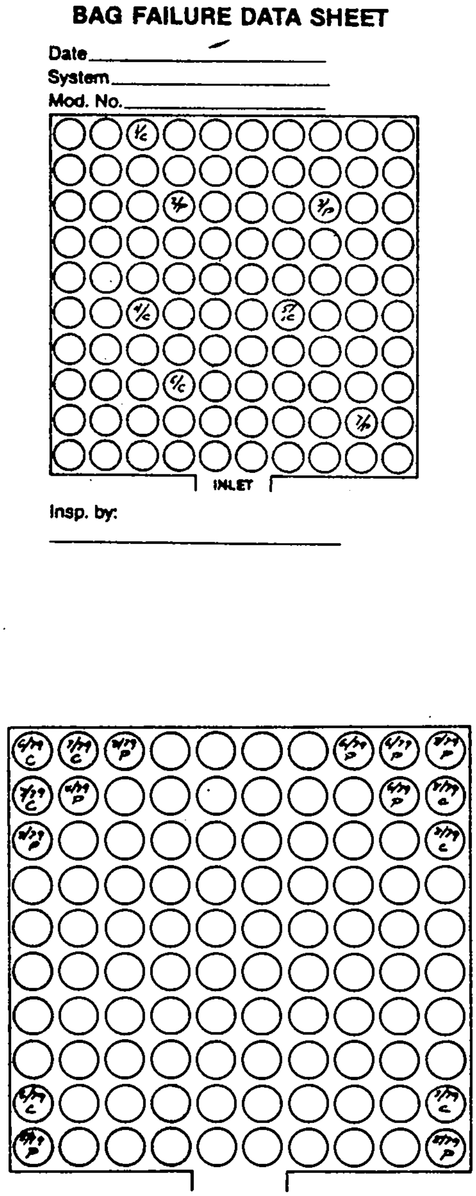


Figure 4.4-24. Bag failure location records. (Courtesy of Richard P. Bundy, Standard Havens, Inc.)

pattern which could be due to a large variety of problems. Symptoms of a baffle problem are shown in the lower figure. In addition to these figures, a simple elevation sketch of each bag removed should be prepared showing the location and type of damage. Another set of diagnostic records which has proven useful is a record of the frequency of bag failures. This can be used to identify a condition which has arisen recently or when a set of bags is reaching the end of the useable life.

REFERENCES

1. Billings, C. and J. Wilder, (GCA Corporation, Boston). Handbook of Fabric Filter Technology, Vol. I. Prepared for U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. Publication No. APTD-0690.

2. Theodore, L. and A. J. Buonicore. Industrial Air Pollution Control Equipment for Particulates. CRC Press. Cleveland. 1976.

3. Perkins, H. C. In: Air Pollution, A. Stern (ed.). New York, McGraw-Hill. 1974.

4. Paretsky, L.L., Theodore R. Pfeffer, and A.J. Squires. J. Air Pollution Control Association. 21:4. April 1971.

5. Anderson, D.M. and L. Silverman. Harvard Air Cleaning Laboratory. AEC Report No. NYO-4615. 1958.

6. Donavan, R.P., J. H. Turner, and J. H. Abbott. Passive Electrostatic Effects in Fabric Filtration. Second Symposium on the Transfer and Utilization of Particulate Control Technology. In: Vol. 1. Control of Emissions from Coal Fired Boilers. F. P. Venditti, J. A. Armstrong, and M. Durham (ed.). U.S. Environmental Protection Agency Publication No. EPA-600/9-80-039a. September 1980. pp. 476-493.

7. Donavan, R.P., R.L. Ogan, and J.H. Turner. The Influence of Electrostatically Induced Cage Voltage Upon Bag Collection Efficiency During the Pulse-jet Fabric Filtration of Room Temperature Flyash. In: Proceedings of the Third Symposium on Fabric Filters for Particle Collection. U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. EPA-600/7-78-087. June 1978.

8. Frederick, E. J. of the Air Pollution Control Association, 24: 1164-1168. December 1974.

9. Frederick, E. Chemical Engineering. 68: 107. June 1971.

10. Turner, J. Extending Fabric Filter Capabilities. J. of the Air Pollution Control Association. 24: 1182-1187. December 1974.

11. Enson, D. S., R. G. Hooper, and R. W. Schech. Determination of the Fractional Efficiency, Opacity Characteristics, Engineering and Economic Aspects of a Fabric Filter Operating as a Utility Boiler. Electric Power Research Institute. Report EPRI FP-297. November 1976.

12. Dennis, R. and H. Klemm. Modeling Coal Fly Ash Filtration with Glass Fabrics. Third Symposium on Fabric Filters for Particulate Collection, N. Surprenant. U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. EPA-600/7-78-087. June 1978. pp. 13-40.

13. Dennis, R. and H. A. Klemm. Fabric Filter Model Format Change, Vol. I, Detailed Technical Report. GCA Report to U.S. Environmental Protection Agency, Contract No. 68-02-2607, Task No. 8. GCA Report GCA-TR-78-51-G(1), January 1969.

14. Hall, R. R., R. Dennis, and N. F. Surprenant. Fibers, Fabrics, Face Velocity and Filtration. A Specialty Conference on the User and Fabric Filtration Equipment III. E. R. Fredrick, (ed.). APCA Specialty Conference Proceedings. 1978. pp. 156-169.

15. Dennis, R. H. A. Klemm. Verification of Projected Filter System Design and Operation. pp. 143-160. Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. 2, Fabric Filters and Current Trends in Control Equipment. F. P. Venditti, J. A. Armstrong, and M. Durham, (ed.). U.S. Environmental Protection Agency. Publication No. EPA-600/7-79-044b. February 1979.

16. Leith, D., M. W. First, M. Ellenbecker, and D. D. Gibson. Performance of a Pulse-jet Filter at High Filtration Velocities. In: Symposium on the Transfer and Utilization of Particulate Control Technology: Vol. 2, Fabric Filters and Current Trends in Control Equipment. F. P. Venditti, J. A. Armstrong, and M. Durham, (ed.). U.S. Environmental Protection Agency. Publication No. EPA-600/7-79-044b. February 1979. pp. 11-26.

17. Leith, D. and M. J. Ellenbecker. Theory for Penetration in a Pulse-jet Cleaned Fabric Filter. Paper 80-30.1. Presented at the 73rd Annual Meeting of the Air Pollution Control Association. Montreal, Quebec. June 22-27, 1980.

18. Dennis, R., J. W. Wilder, and D. L. Harman. The Mechanics of Pulse-jet Filtration, Paper 80-30.6. Presented at the 73rd Annual Meeting of the Air Pollution Control Association. Montreal, Quebec. June 22-27, 1980.

19. Theodore, L. and J. Reynolds. Performance Equations Describing Effects of Bay Farline on Baghouse Outlet Loadings. Presented at the Air Pollution Control Association Annual Meeting. Cincinnati, Ohio. June 24-29, 1979.

20. Perkins, R. P. The Case for Fabric Filters on Boilers. Semiannual Technical Conference on Air Pollution Equipment. Philadelphia, Pennsylvania. April 23, 1976.

21. Vandenhoeck, P. Cooling Hot Gases Before Baghouse Filtration. Chemical Engineering. Vol. 79, No. 9: 67-70. May 1, 1972.

22. Bergmann, L. New Fabrics and Their Potential Application. J. Air Pollution Control Association. 24: 1187-92. December 1974.

23. Perkins, R. P. State-of-the-art of Baghouses for Industrial Boilers. Presented at the Industrial Fuel Conference. West Lafayette, Indiana. October 5-6, 1972.

24. Rolschau, D. W. Matching a Baghouse to a Fossil Fuel Fired Boiler. In: Symposium on the Transfer and Utilization of Particulate Control Technology: Vol. 2, Fabric Filters and Current Trends in Control Equipment. F. P. Venditti, J. A. Armstrong, and M. Durham, (ed.). U.S. Environmental Protection Agency, Research Triangle Park, N.C., Publication No. EPA-600/7-79-044b. February 1979. pp. 211-217.

25. Brandt, E. F. Operation and Maintenance of Fabric Filters on Coal-Fired Boilers. In: Proceedings: Operation and Maintenance Procedures for Gas Cleaning Equipment. E. R. Fredrick (ed.). APCA Specialty Conference Proceedings. 1980. pp. 153-161.

26. Billings, C. E. and J. E. Wilder. Major Application of Fabric Filters and Associated Problems. Paper No. 15. In: Proceedings of the Symposium on Control of Fine-Particulate Emissions from Industrial Sources. San Francisco, California. January 15-18, 1974. pp. 329-372.

27. Tracy, G. W. Operation and Western Precipitation Fly Ash Baghouses Since Sunbury. In: Proceedings: Operation and Maintenance Procedures for Gas Cleaning Equipment. E. R. Fredrick (ed.). APCA Specialty Conference Proceedings. 1980. pp. 162-181.

28. Mappes, T. E. and R. D. Tems. An Investigation of Corrosion in Particulate Control Equipment. U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. EPA-340/1-81-002. February 1981.

29. Prinz, R. T. Reducing Baghouse Maintenance by Design. Minerals Processing. 11: 8-13. May 1970.

30. E. I. duPont de Nemoursand Company, Bulletin No. E-13544.

31. Menardi and Company. Bulletin. Segundo, California.

32. Pearson, G. L. Experience at Coors with Fabric Filters-Firing Pulverized Western Coal. In: Second Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. 1, Control of Emissions from Coal Fired Boilers, F. P. Venditti, J. H. Armstrong, and M. Durham, (ed.). U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. EPA-600/9-80-039a. September 1980. pp. 359-370.

33. Ladd, K. L. Jr., R. Chambers, S. Kunka, and D. Harman. Objectives and Status of Fabric Filter Performance Study. In: Second Symposium on the Transfer and Utilization of Particulate Control Technology. Vol. 1, Control of Emission from Coal Fired Boilers, F. P. Venditti, F. A. Armstrong, and M. Durham (ed.). U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. EPA-600/9- 0-039a. September 1980. pp. 317-341.

34. Mycock, J. C. A Pilot Plant Study of Various Filter Media Applied to a Pulverized Coal-fired Boiler In: Symposium on the Transfer and Utilization of Particulate Control Technology. Vol. 2, Fabric Filtration Current Trends in Control Equipment. F. P. Venditti, F. A. Armstrong, and M. Durham, (ed.). U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. EPA-600/7-79-044b. February 1979.

35. Simon, H. T. Baghouses. In: Air Pollution Engineering Manual. 2nd Edition, J. A. Danielson (ed.). U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. AP-40. May 1973.

36. Wright, R. J. Customizing Baghouses for Clinker Coolers. Rock Products. November 1972. pp. 94-129.

37. Miller, R. L. Explosion Pressure Relief. In: Proceedings: The User and Fabric Filtration Equipment III. E. R. Fredrick (ed.). APCA Specialty Conference Proceedings. 1978. pp. 98-112.

38. Reinauer, T. V. Guidelines in Application of Explosion Vents. In: Proceedings, The User and Fabric Filtration Equipment IV. E. R. Fredrick (ed.). APCA Specialty Conference Proceedings. 1978. pp. 113-119.

39. Perkins, R. P. and J. F. Imbalzano. Factors Affecting Bag Life Performance in Coal-Fired Boilers. In: Proceedings, The User and Fabric Filtration Equipment III. E. R. Fredrick (ed.). APCA Specialty Conference Proceedings. 1978. pp. 120-144.

40. Szabo, M. F. and R. W. Gerstle. Operation and Maintenance of Particulate Control Devices on Coal-Fired Utility Boilers, U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. EPA 600/2-77-129. July 1977. pp. 3-85.

41. Strauss, W. Industrial Gas Cleaning. Pergamon Press. New York, 1975.

42. Smith, G. L. Engineering and Economic Considerations in Fabric Filters. J. Air Pollution Control Association. 24: 1154-56.

43. Bundy, R. P. Operations and Maintenance of Fabric Filters. In: Proceedings, Operation and Maintenance Procedures for Gas Cleaning Equipment. E. R. Fredrick. (ed.). APCA Specialty Conference Proceedings. 1980. pp. 139-152.

44. Dennis, R. and J. E. Wilder. Factors in the Collection of Fine Particulate Matter with Fabric Filters. Paper No. 17. In: Proceedings, Symposium on Control of Fine-Particulate Emissions from Industrial Sources. San Francisco, California. January 15-18, 1974. pp. 385-424.

4.5 WET SCRUBBERS

Wet scrubbers comprise a set of control devices with similar particle collection mechanisms, primarily: inertial impaction and Brownian diffusion. Accordingly, these scrubber systems generally exhibit strong particle-size-dependent performance. Among scrubber types substantial differences exist with regard to their effectiveness, the greatest differences occurring in the particle size range of 0.1 to 2 μmA.

The various types of commercially available wet scrubbers are described in Section 4.5.1. Fundamental operating principles are presented in Section 4.5.2. Parameters of interest and performance limits are discussed. Emphasis is on the capability for collection of particles smaller than 5 μmA in diameter.

Considerable progress made in the understanding of wet scrubber performance since the first edition of this document was published is reflected in practical design considerations in Section 4.5.3. Operation and maintenance factors that enhance long-term performance are presented in Section 4.5.4.

4.5.1 Types of Particulate Scrubbers

In this discussion major categories of scrubbers are grouped on the basis of similar mechanisms. In Table 4.5-1, major categories of scrubbers are listed in order of increasing performance capabilities and energy requirements.

Scrubber liquids are used for particle collection in several distinct ways. The most common method is to generate droplets, which are then intimately mixed with the gas stream. Particles are also collected on water layers or sheets surrounding of packing material by directing the particle-laden gas stream through an intricate path around the individual packing elements. A third method is to pass high-velocity gas through a vapor to generate "jets" of liquid to collect particles. This is the least common of the three liquid characteristics.

4.5.1.1 Preformed Spray Scrubbers. Preformed spray scrubbers require the least energy of the various scrubbers, and they consequently allow the

TABLE 4.5-1. MAJOR TYPES OF WET SCRUBBERS[a]

Category	Particle capture mechanism	Liquid collection mechanism	Types of scrubbers
Preformed-spray	Inertial impaction	Droplets	Spray towers Cyclonic spray towers Vane-type cyclonic towers Multiple-tube cyclones
Packed-bed scrubbers	Inertial impaction	Sheets, droplets (moving bed scrubbers)	Standard packed-bed scrubbers Fiber-bed scrubbers Moving-bed scrubbers Cross-flow scrubbers Grid-packed scrubbers
Tray-type scrubbers	Inertial impaction Diffusional impaction	Droplets, jets, and sheets	Perforated-plate Impingement-plate scrubbers Horizontal impingement-plate (baffle) scrubbers
Mechanically aided scrubbers	Inertial interception	Droplets and sheets	Wet fans Disintegrator scrubbers
Venturi and orifice scrubbers (gas atomized scrubbers)	Inertial impaction Diffusional impaction	Droplets	Standard venturi scrubbers Variable-throat venturi scrubbers: flooded disc, plumb bob, movable blade, radial flow, variable rod Orifice scrubbers

[a]List not intended to be all inclusive.

highest particulate penetration, especially of small-diameter particles. Most preformed spray scrubbers are highly efficient only for particles larger than 5 μmA in diameter.[1-3]

4.5.1.1.1 Spray tower. A spray tower is the simplest type of scrubber, consisting of a chamber containing an array of spray nozzles (Figure 4.5-1).

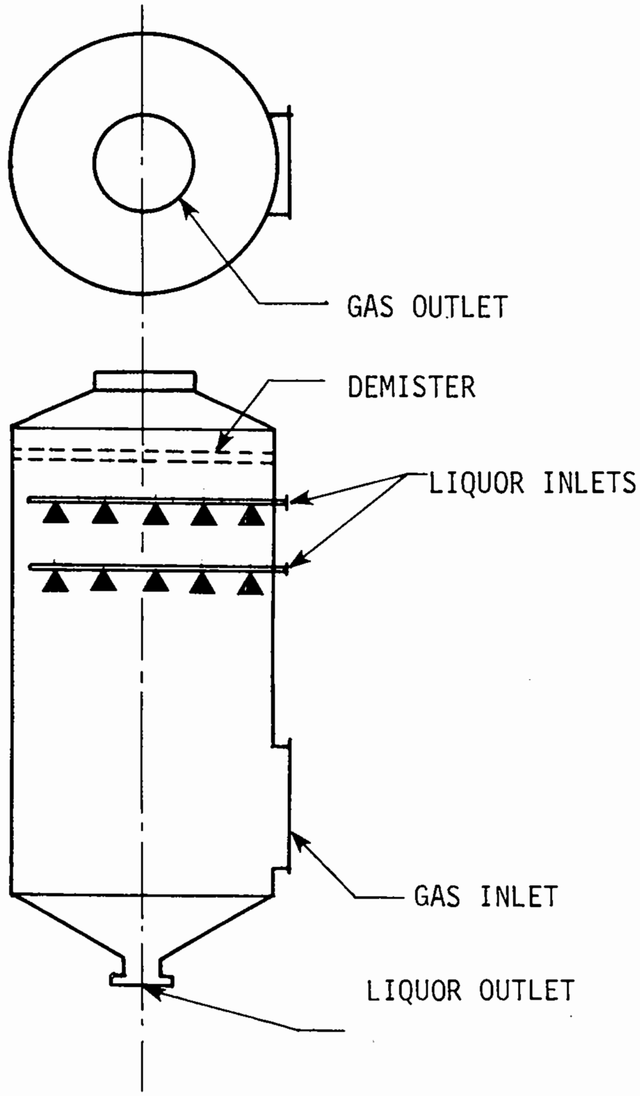


Figure 4.5-1. Spray tower scrubber

Particulate-laden gases pass vertically up through the tower while the liquid droplets fall by gravity down through the gas flow. Particles collide with the droplets, are collected into the liquor, and carried out of the scrubber. Collection is limited by the terminal settling velocity of the droplets. The spray tower scrubber has low particle removal capability, but it is often useful for treating effluent gas streams having high mass loadings of large diameter particulate matter.[4]

4.5.1.1.2 Cyclonic spray tower. A cyclonic spray tower is similar to the spray tower scrubber except that the gas stream is given a spiral motion. In one typical configuration particulate-laden gases enter the scrubber vessel tangentially at the bottom and pass upward in a spiral motion around a centrally located array of spray nozzles. Droplet migration is crosscurrent to the gas flow. Cyclonic spray towers generally operate with a static pressure drop of 1 to 2 kPa.[3] Penetration of particles less than 2 µmA in diameter is typically quite high.[5]

4.5.1.1.3 Vane type Cyclonic Spray Tower. A vane-type cyclonic scrubber utilizes a system of vanes rather than a tangential inlet to impart cyclonic motion (Figure 4.5-2).

4.5.1.1.4 Multiple-tube Cyclones. Another type of cyclonic scrubber consists of multiple miniature tubes, each with a separate liquid supply. In this design the gases flow in a downward pattern in contrast to the upward flow of other cyclones.

4.5.1.2 Packed Bed Scrubbers. In the typical packed-bed scrubber liquid introduced near the top trickles down through the packed bed. The liquid flow spreads over the packing into a film with a large surface area (Figure 4.5-3). The liquid can be introduced concurrent or crosscurrent with the gas flow. Packing materials include raschig rings, pall rings, berl saddles, tellerettes, intalox saddles, and materials such as crushed rock.[3] Packed beds are also constructed with metal grids, rods, or fiberous pads. These scrubbers are often used for gas transfer or gas cooling, both of which are facilitated by the large liquid surface area provided on the packing.[3]

Plugging of a bed can occur if the gas to be treated is too heavily laden with solid particles.[3,4] A general rule for many applications is to limit the use of packed beds to service in which particulate concentrations are less than 0.45 g/m^3. Moving-bed scrubbers that have less propensity for plugging (Figure 4.5.4) are packed with low-density plastic spheres, which are free to move within the packing retainers.

Packed-bed scrubbers are reported to have low penetration for particle sizes down to 3 µmA and can sometimes remove a significant fraction of particulate in the range of 1 to 2 µmA. The standard countercurrent

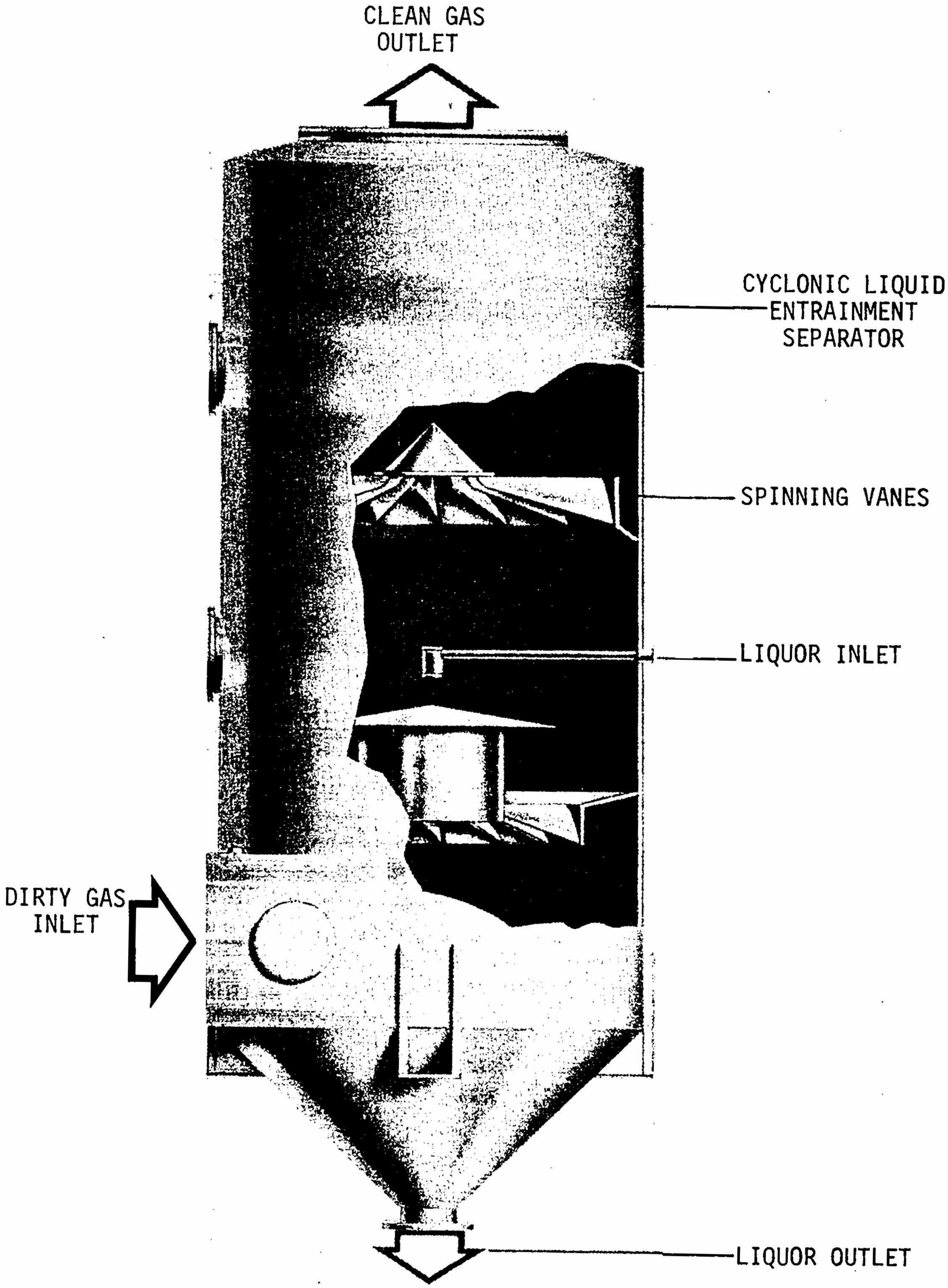


Figure 4.5-2. Vane type scrubber (courtesy of the Ducon Company, Inc.).

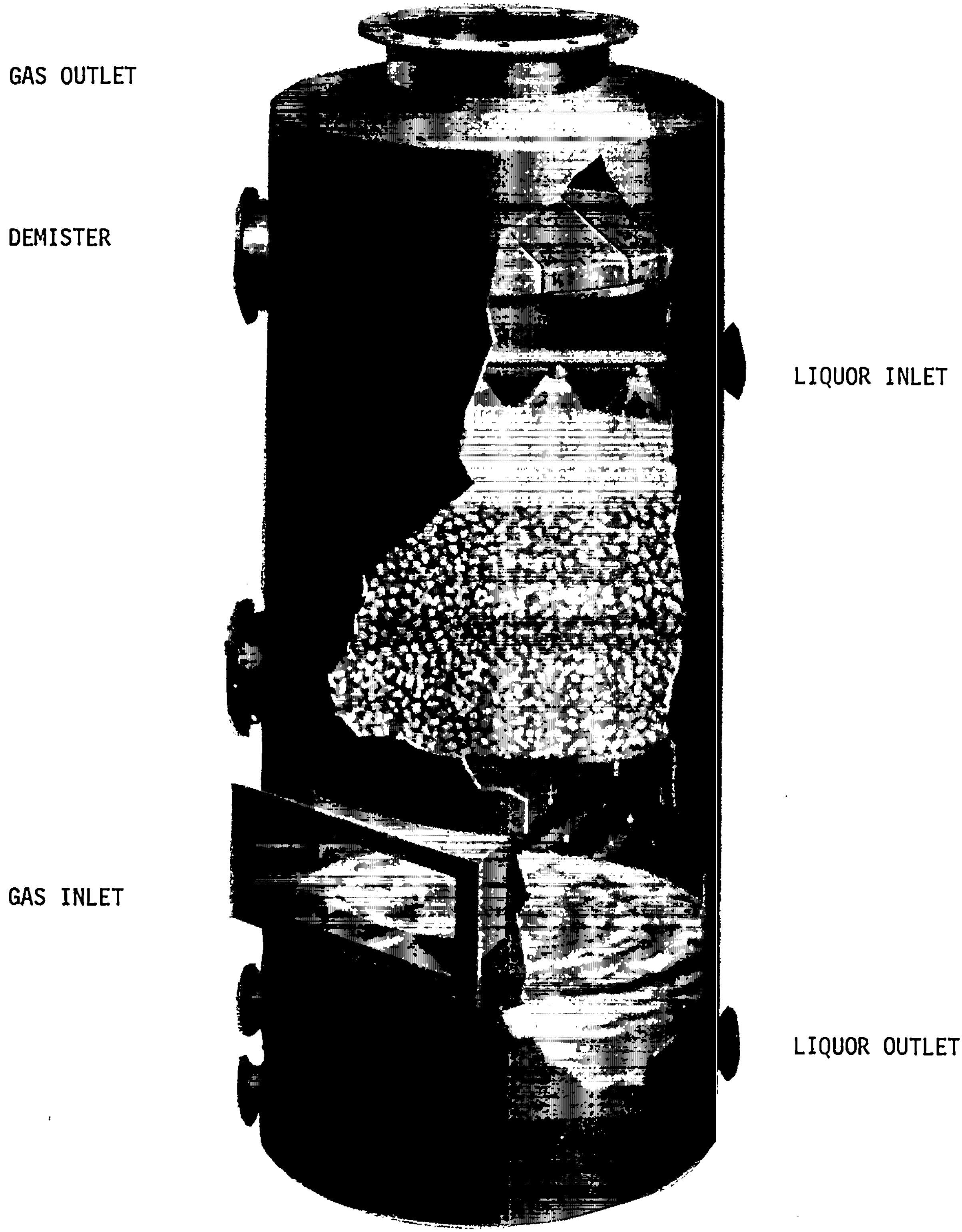


Figure 4.5-3. Packed tower scrubber (courtesy of Air Pollution Industries, Inc.)

Figure 4.5-4. Moving-bed scrubber (courtesy of UOP - Air Correction Division).

arrangement requires the greatest liquid flow and can best handle heavier loadings. Crosscurrent packed-bed scrubbers require much less liquid flow, usually operate at lower static pressure drops, and rarely suffer from plugging. Concurrent packed-bed scrubbers are reportedly more efficient than other packed-bed scrubbers for the smaller particulates, but they typically operate at higher pressure drops.

4.5.1.3 Tray-Type Scrubbers. A tray-type scrubber typically consists of a vertical tower with one or more perforated plates mounted inside transversely to the shell. In such a scrubber the liquid flows from top to bottom, and the gas flows from bottom to top. Gases in the scrubber mix with the liquid passing through the openings in the plates.

The perforated plates of a tray-type scrubber are often equipped with impingement baffles or bubble caps over the perforations (Figure 4.5-5). The gas passing upqard through a perforation is forced to turn 180 degrees into a layer of liquid. The gas bubbles through the liquid, and particulate is collected in the liquid sheet. The impingement baffles are below the liquid level on the perforated plates and are, therefore, continuously washed clean of collected particles. Penetration through a typical impingement plate is low for particles larger than 1 μmA,[3] but penetration of submicrometer particulate is higher than with some higher-energy scrubbers. Pressure drop through a typical baffle plate is roughly 0.4 kPa per stage.[3] Addition of plates increases the scrubber pressure drop, but does not proportionally decrease the penetration of submicrometer particulate.[6]

One additional variation of the tray scrubber is the horizontal baffle-type scrubber. In this type of scrubber the direction of gas flow is horizontal and the baffle section is mounted vertically in the scrubber. The scrubbing liquid is introduced concurrently with the gas.

4.5.1.4 Mechanically Aided Scrubbers. The mechanically aided scrubbers utilize a mechanical rotor or fan to shear the scrubbing liquid into dispersed droplets. These scrubbers use a specially designed stator and rotor arrangement to produce very finely divided liquid droplets that are effective in capture of fine particulate. The low penetration of fine particulate, however, is achieved at a high energy cost.[1-3] Because both wet-fan and disintegrator-

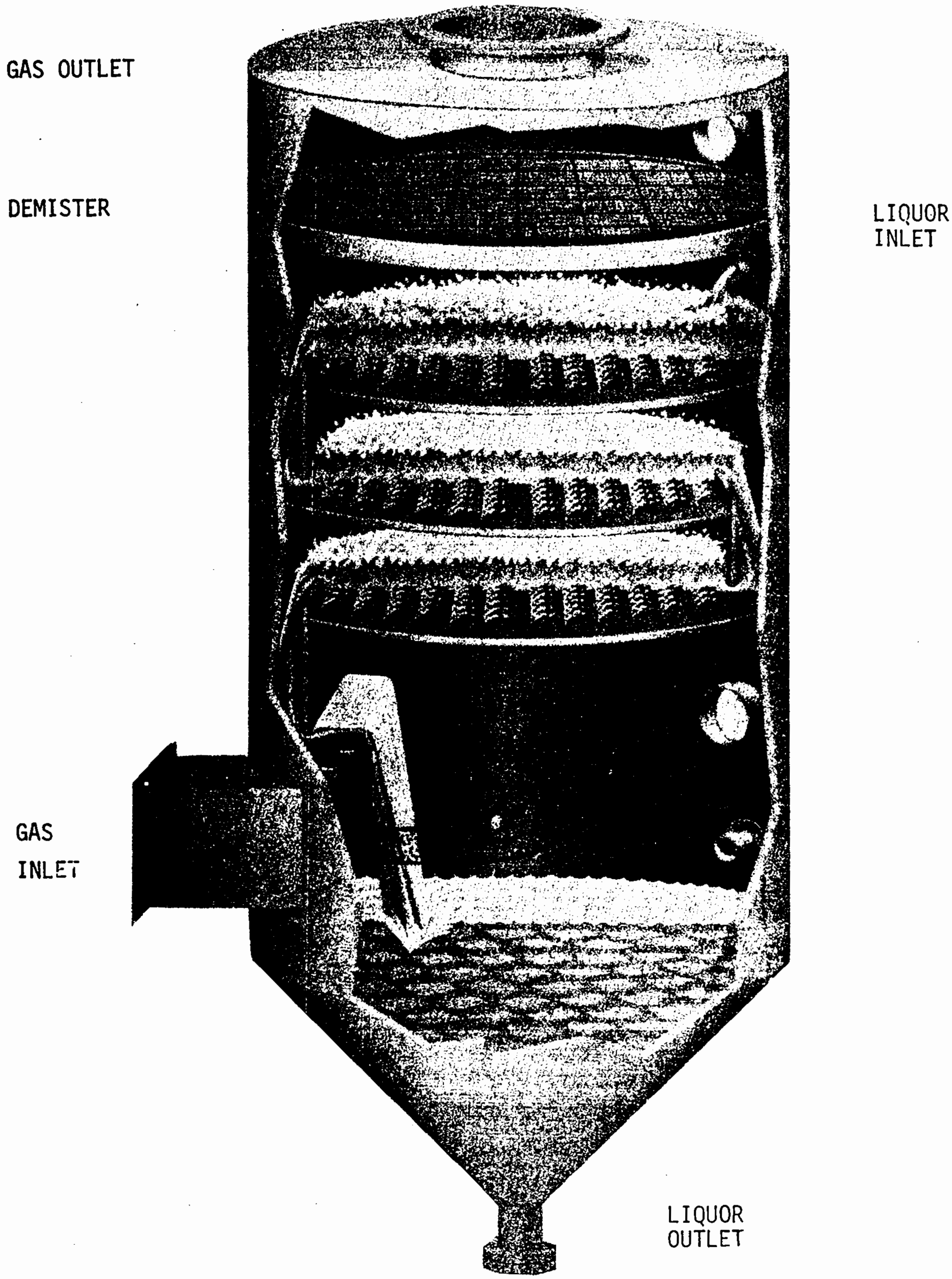


Figure 4.5-5. Tray scrubber (courtesy of the Koch Engineering Company).

type mechanically aided scrubbers are subject to particulate buildup or erosion at the rotor blades, they are often preceded by precleaning devices for removing coarse particulate.[1,4] Mechanically aided scrubbers generally do not perform well in air containing more than 1 g/m^3 of particulate.[1]

4.5.1.5 Venturi and Orifice Scrubbers. Venturi and orifice scrubbers are perhaps the most common particulate removal devices, in part because they allow lower penetration of small particles than most other types of scrubbers. These scrubbers accomplish superior particulate collection by generating small liquid droplets in the turbulent zone in a manner that creates a high initial relative velocity between the droplets and the particulate. Inertial impaction capture of particulate by the scrubbing liquid is more efficient in these highly turbulent processes, but a price is paid in energy consumption to achieve the low penetration.

4.5.1.5.1 Venturi scrubbers. The simple venturi scrubber, often called a gas atomizing spray scrubber, consists of a series of sprays upstream from a converging and diverging "throat" section (Figure 4.5-6). As the gas approaches the venturi throat, the velocity and turbulence increase. The high gas turbulence atomizes the liquid into small droplets and increases interaction between the droplets and the particulate. Pressure drops in venturi scrubbers can range from less than 1 to 40 kPa.

4.5.1.5.2 Variable-throat venturi scrubbers. Pressure drop and venturi performance are partially dependent on gas velocity through the venturi. Several variations of the standard venturi scrubber have been developed to allow the venturi throat dimensions to be changed as the rate of gas flow changes. Among these scrubbers are the plumb-bob venturi, the flooded-disc venturi, the moveable-blade venturi, the radial-flow venturi, and the variable-rod venturi. Several of these venturi throats are illustrated in Figure 4.5-7.

4.5.1.5.3 Orifice scrubber. In an orifice scrubber, sometimes referred to as an entrainment or self-induced spray scrubber, the gas stream passes over a pool of scrubbing liquid at high velocity just before entering an orifice. The high velocity of the gas induces ("entrains") a spray of scrubbing liquid droplets, which interact with the particulate in and immediately after the orifice. Orifice scrubbers have moderate pressure drops (0.8 to 4.0 kPa) and low penetration of particulate 2 to 3 μmA in diameter and larger.

4.5.2 Operating Principles of Particulate Scrubbers

The fundamental principles that govern particle penetration and total static pressure drop are examined both in a general manner and with respect to classes of wet scrubbers.

4.5.2.1 Penetration. Particulate matter collection in wet scrubbers is highly size-dependent because of the fundamental characteristics of the inertial impaction and diffusion processes. Figure 4.5-8 illustrates the theoretical single-droplet collection efficiency resulting from these two phenomenon as calculated by Crawford[7] for an example case. This particular example illustrates a predicted minimum collection efficiency reached at 0.1-μmA particles; the size at which both mechanisms become ineffective. This general curve applies to most scrubbers; however, the location and magnitude of the efficiency minimum depends on the specific unit.

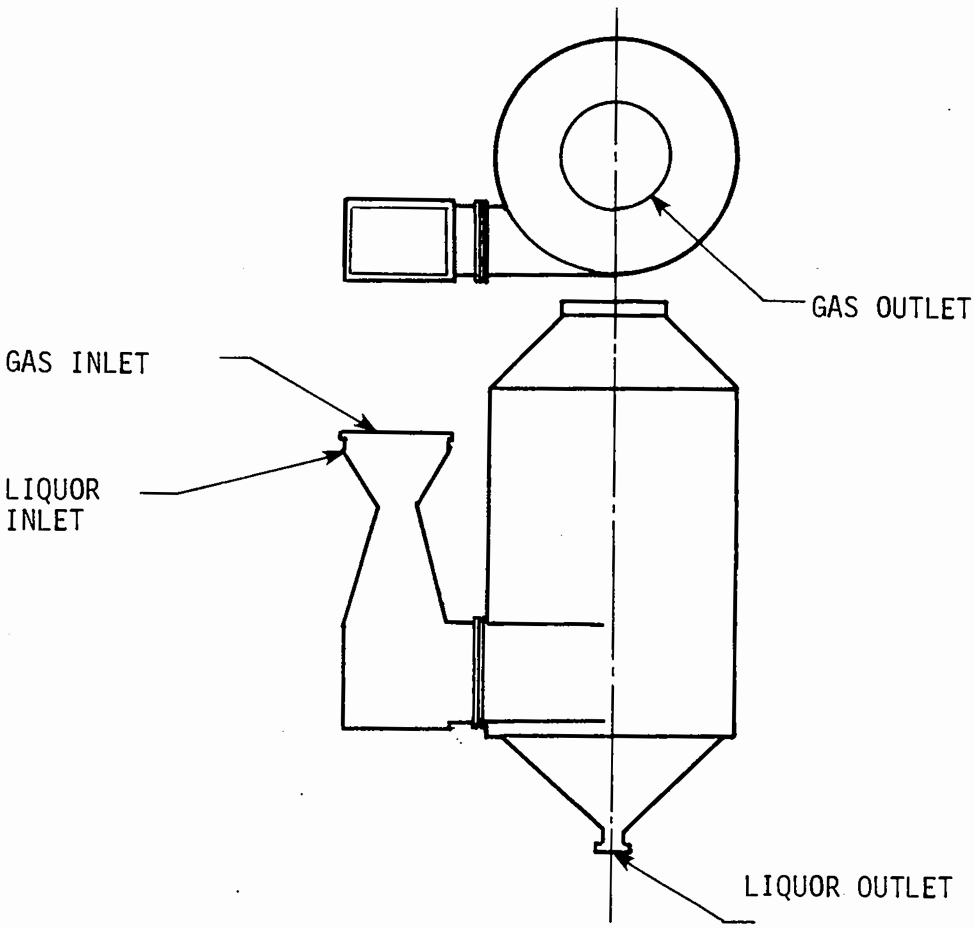


Figure 4.5-6. Venturi scrubber.

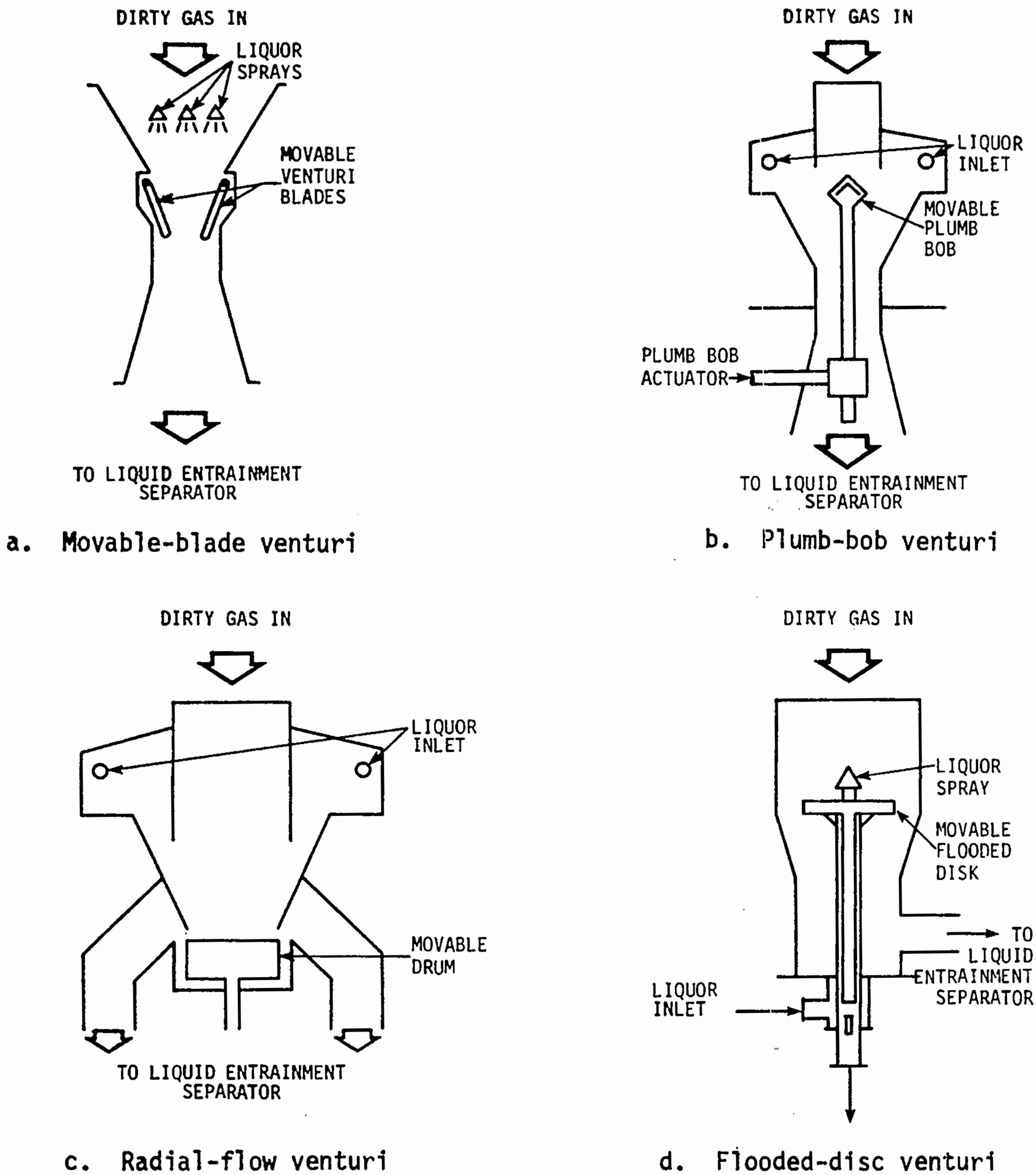


Figure 4.5-7. Throat sections of variable throat venturi scrubbers (courtesy of Industrial Gas Cleaning Institute, Inc.).

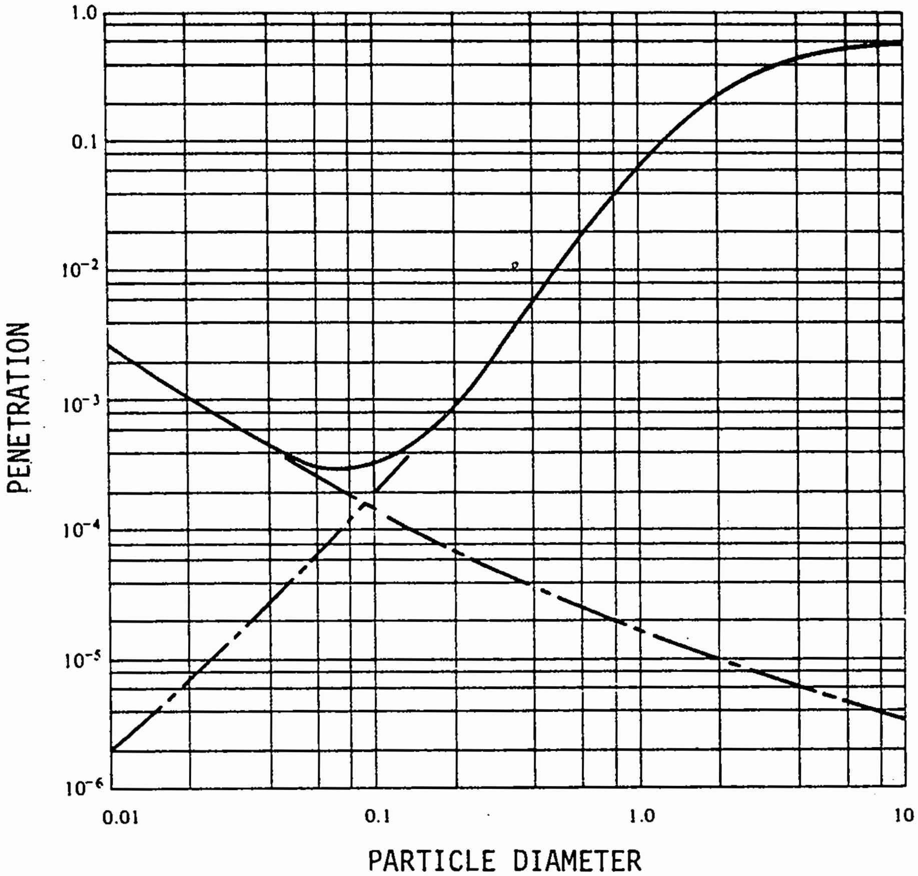


Figure 4.5-8. Theoretical single-drop collection efficiency due to diffusion and impaction (reprinted by permission: Crawford, M. Air Pollution Control Theory, McGraw Hill Co., New York, 1976).

Analysis of the particle collection capability of wet scrubbers can be based on (1) the fundamental particle collection mechanisms and (2) the empirical contact power approach. The latter method is based on the premise that penetration is proportional to the power expended in the scrubber.[8-13]

This premise is logical because high energy consumption implies high relative gas-water velocities, high water utilization, and fine droplet formation, all of which favor impaction, the dominant collection mechanism. Limitations of the contact power analysis can be attributed to the difficulty of handling nonideal operating conditions such as poor gas-liquid distribution and particle shattering during high-energy scrubbing. Also, this type of analysis is not amenable to situations in which particle collection mechanisms other than inertial impaction are important.

Penetration analyses based on the fundamental particle collection mechanisms involve the identification of the dominant physical phenomenon leading to particle capture. Following is a partial list of the collection mechanisms.

Collection medium	Capture phenomenon
Droplets	Inertial impaction Interception Brownian diffusion
Liquid sheets (layers)	Inertial compaction Interception Brownian diffusion Electrostatic attraction
Liquid sheets	Inertial impaction Interception Diffusion
Bubbles	Inertial impaction Interception Brownian diffusion Electrostatic attraction

For each control device, penetration relationships are based on anticipated particle collection mechanisms. The accuracy of the resulting equations depends on the proper assignment of the mechanisms and on the accuracy of the mechanism expressions. Penetration expressions presented in the Scrubber Handbook[3] for selected wet scrubbers are provided in the following paragraphs.

4.5.2.1.1 Preformed-spray scrubbers. The most effective particle collection mechanism is inertial impaction to liquid droplets. The penetration calculations depend on droplet size and flow characteristics (i.e., countercurrent, cocurrent, and crossflow). For countercurrent conditions, the following equation is applicable:

$$P_i = e - \left[\frac{0.75\, v_t\, \eta_i\, Z}{r_d(v_t - v_G)}\right]\left[\frac{Q_l}{Q_g}\right] \qquad \text{(Equation 4.5-1)}$$

where

v_t = droplet terminal settling velocity, cm/s.
η_i = impaction parameter, dimensionless.
Z = scrubber height, cm.
r_d = droplet radius, cm.
v_G = gas superficial velocity, cm/s.
$\frac{Q_l}{Q_g}$ = liquid-to-gas ratio, dimensionless.

The parameter η_i is calculated according to Equation 4.5-2.

$$\eta_i = \left[\frac{Ki}{(K_i + 0.7)}\right]^2 \qquad \text{(Eq. 4.5-2)}$$

where

K_i = impaction parameter for particles having aerodynamic diameters of i.

The variables that control the penetration rates from a preformed-spray scrubber include scrubbing zone height, superficial gas velocity, particle aerodynamic diameter, liquid-to-gas ratio, and spray droplet size. These variables are equally important in cocurrent and crosscurrent preformed spray scrubbers, which are discussed further in Calvert et al.[3] These scrubber types share the characteristic penetration curve presented earlier for impingement-plate scrubbers.

4.5.2.1.2 Packed-bed scrubbers. The packed-bed scrubber primarily utilizes inertial impaction of particles on water "sheets" on the packing material. Turbulent diffusion may contribute some additional particle capture in the <0.2-µmA size range. Equation 4.5-3 is based strictly on impaction.

$$P_i = e - \left[\frac{\pi}{2(j+j^2)\ (\varepsilon - H_d)}\right] \left[\frac{Z}{d_c}\right] K_i \qquad \text{(Eq. 4.5-3)}$$

where

P_i = penetration value for a specific particle size, dimensionless.
j = "channel" width factor, dimensionless.
ε = bed porosity, dimensionless.
H_d = liquid holdup in bed, dimensionless.
Z = height of packed section, m.
d_c = packing element diameter, m.
K_i = inertial impaction parameter, dimensionless.

The parameter K_i is common to most penetration equations applicable to control devices based on impaction. The higher the value of K_i, the higher the collection efficiency for particles with an aerodynamic diameter of i. The impaction parameter is a strong function of particle size, as indicated in Equation 4.5-4.

$$K_i = \left[\frac{v_g}{9\mu\ \ d_c}\right] \left[d_i\right]^2 \qquad \text{(Eq. 4.5-4)}$$

where

v_g = gas velocity through the bed, calculated as the volumetric flow rate divided by the scrubber cross-sectional area, cm/s.
μ = gas viscosity at actual temperature, g/s-m.
d_i = aerodynamic particle diameter i, $\mu m\ (g/cm^3)^{0.5}$.

Combining Equations 4.5-3 and 4.5-4 provides a means of calculating penetration for specific particle sizes, which can then be added to determine total penetration. Typical values for the parameter, j, are 0.160 to 0.190.[3] The smaller the packing material, the lower j should be. Bed porosity, ε, also depends on the packing size and normally varies from 0.60 to 0.95.[3] Calvert et al. list bed porosities for use in selecting types and sizes of packing. Liquid holdup is normally assumed to be negligible.[3]

Figure 4.5-9 presents a typical penetration curve for a packed tower. This theoretical curve is based on the above mathematical relationships and use of the parameter values specified. It is apparent that there is a very

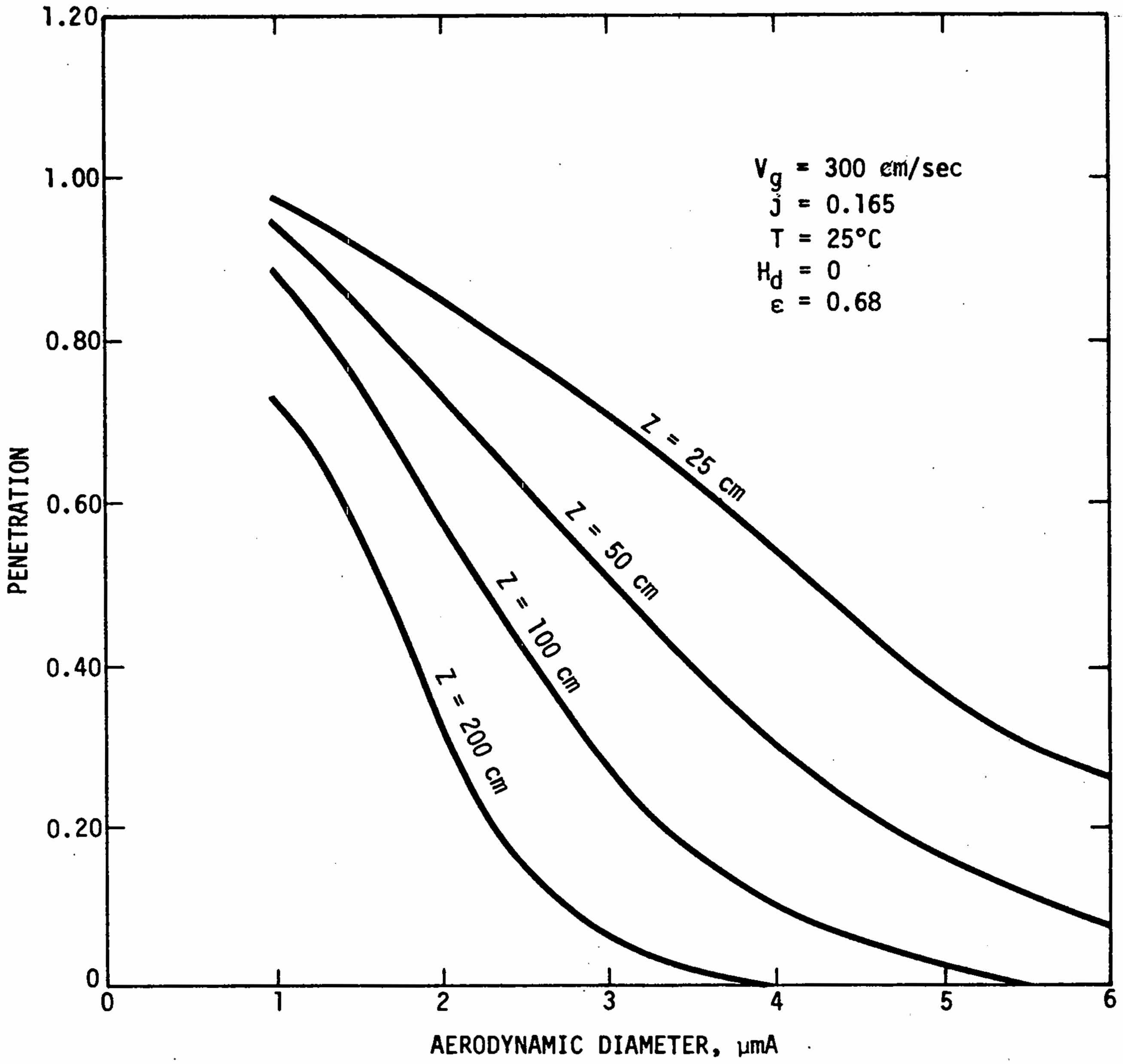


Figure 4.5-9. Theoretical penetration curves for various-sized packed-bed scrubbers.

strong interdependence between particle size and penetration. Actual penetration values for a specific facility (at a specific time) might vary by more than a factor of 2 from those calculated from Equation 4.5-3. Nevertheless, the penetration curve will resemble that of Figure 4.5-11. Generally, packed-bed scrubbers are relatively ineffective for sources with a major fraction of the particulate emissions in the <2.0-μmA size range.

Optimization of an existing unit could be done by changing gas velocity, bed height, and packing type. The liquid-to-gas ratio (L/G) is not a controlling factor with the packed bed scrubber, as it is with other scrubber types.

4.5.2.1.3 Tray-type scrubbers. An impingement-plate scrubber is typical of penetration conditions created in a tray-type scrubber. The theoretical penetration of this type of scrubber is illustrated in Figure 4.5-10. The dominant particle-collection mechanism is inertial impaction to droplets formed as the gas stream passes the impingement hole. The penetration rate of particles of aerodynamic diameter i is calculated according to Equation 4.5-5.

$$P_i = 1 - \left[\frac{K_i}{K_i + 0.7}\right]^{0.5} \qquad \text{(Eq. 4.5-5)}$$

where

P_i = penetration through an impingement plate scrubber of a particle with aerodynamic diameter of i, dimensionless.

K_i = impaction parameter of a particle with aerodynamic diameter of i, dimensionless.

The impaction parameter is calculated by use of Equation 4.5-4 with the velocity term being the velocity of the gas at the vena contracta after it passes through the hole. Calvert et al. suggest using a typical vena contacta velocity of 1.43 times the gas velocity in the hole.[3] In Equation 4.5-4 the "collector" diameter is taken as diameter of the impingement hole.

The theoretical penetration derived by use of Equation 4.5-5 is shown in Figure 4.5-10. A comparable data set[14] for a full-scale impingement scrubber or a rotary salt dryer is shown in Figure 4.5-11.

Performance of the impingement plate scrubber is controlled by the same basic factors as those of other wet scrubbers utilizing inertial impaction to water droplets. Those factors are aerodynamic particle size, relative velocities of particles and droplets, and liquid-to-gas ratio. The impingement plate scrubbers and the entire family of tray scrubbers operate the inertial impaction mechanisms somewhat less effectively than the venturi scrubbers; accordingly, they allow higher penetration in the range of 0 to 1 μmA.

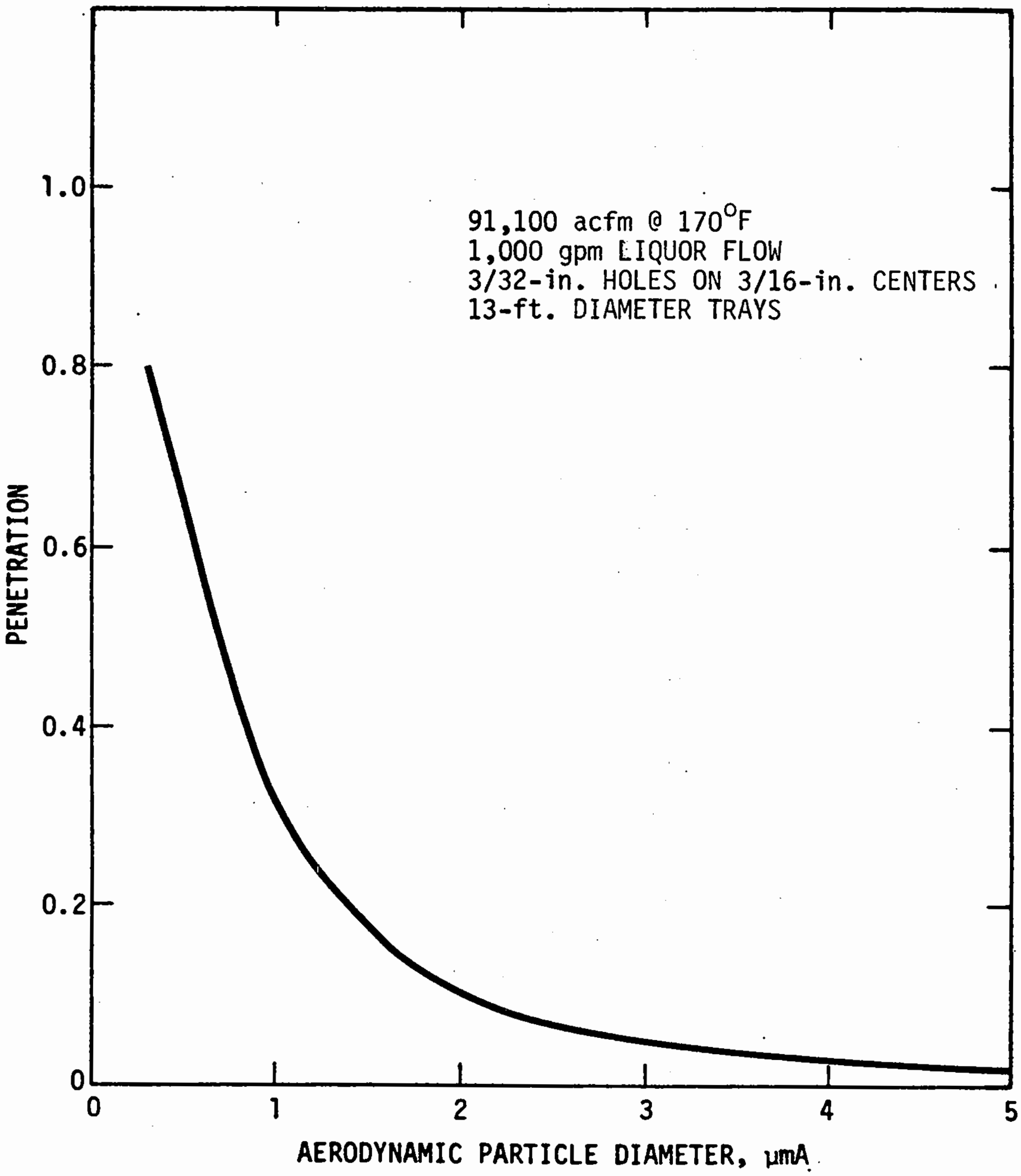


Figure 4.5-10. Theoretical penetration curve for impingement plate scrubber.

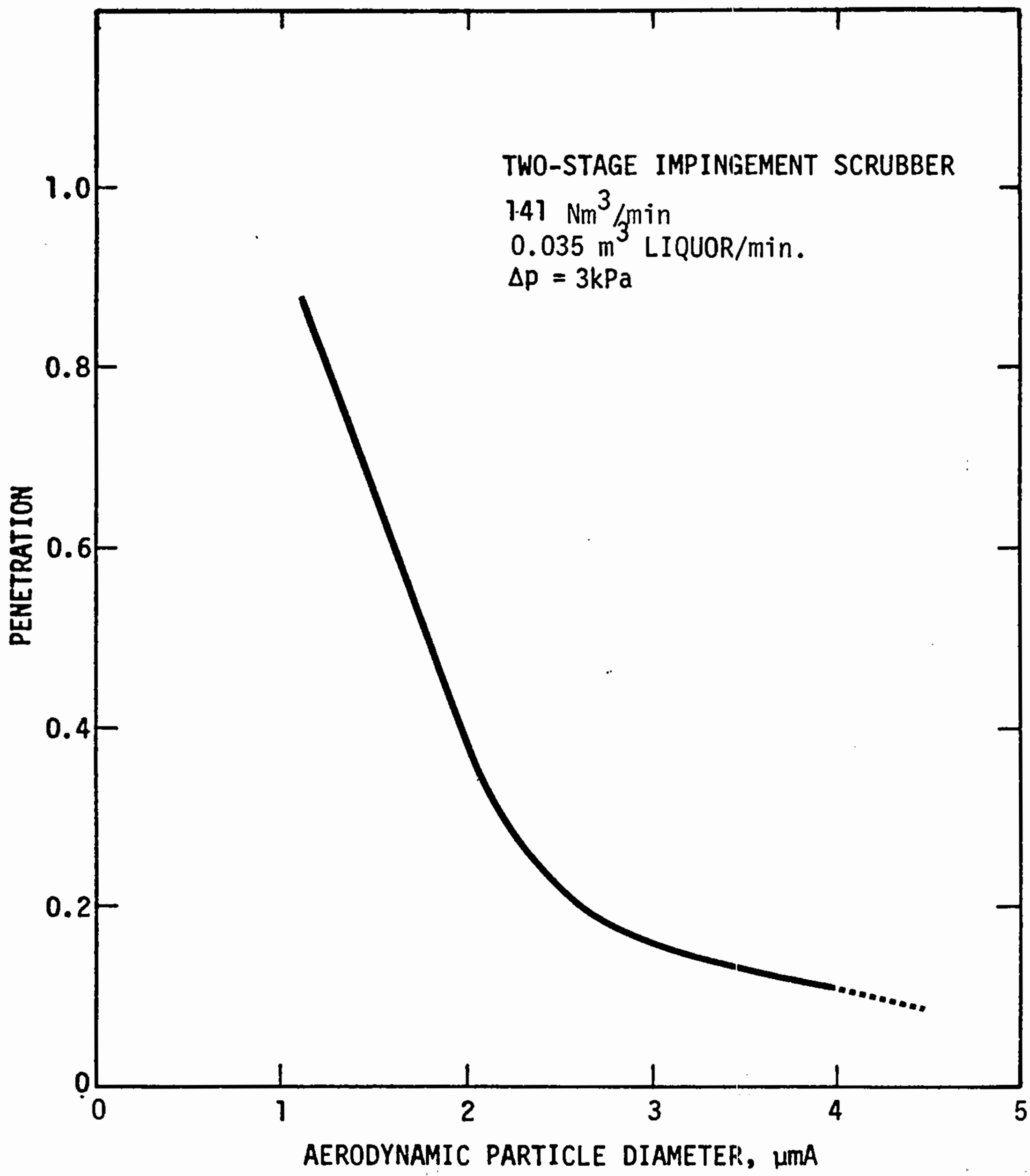


Figure 4.5-11. Penetration curve for an impingement plate scrubber on a rotary salt dryer.

4.5.2.1.4 Venturi and Orifice Scrubbers The penetration equation developed by Calvert et al. for venturi and orifice scrubbers is Equation 4.5-6, based on inertial impaction of particles onto water droplets.[3]

$$P_i = e^{-\left[\left(\frac{0.036 \quad \rho_l d_d V_g}{\mu_g}\right)\left(\frac{Q_l}{Q_g}\right)\right]\left[-0.7-k_i f+ 1.4 \ln\left(\frac{k_i f \; + 0.7}{0.7}\right)+\left(\frac{0.49}{k_i f \; +0.7}\right)\right]\left[\frac{1}{k_i}\right]}$$

where

P_i = penetration value for particles with aerodynamic diameters of i.
ρ_p = droplet density, kg/m^3.
d_d = droplet diameter, m.
v_g = superficial gas velocity in venturi throat, m/s.
μ = gas viscosity, kg/m-s.
Q_l/Q_g = liquid-to-gas ratio, dimensionless.
k_i = impaction parameter, dimensionless.
f = nonuniformity correction factor, dimensionless.

Selection of a proper f factor is important in making an accurate performance prediction. Calvert et al. suggest f values ranging from a low of 0.10 to a high of 0.70 with typical values being 0.25 to 0.50.[3] Low values are applicable to scrubbers having high liquid-to-gas ratios and/or having hydrophobic particles. Increasing f values leads to substantially reduced penetration predictions. The droplet diameter is normally calculated using the equation of Nukiyama and Tanasawa presented below as Equation 5.4-7.

$$d_d = \left(\frac{50}{V_g}\right) + 91.8 \cdot \left(\frac{Q_l}{Q_g}\right)^{1.5}$$

where

d_d = Sauter mean droplet size, cm.
V_G = gas velocity in venturi throat, cm/s.
Q_l/Q_g = liquid-to-gas ratio, dimensionless.

Boll et al.[15] determined that Eq. 4.5-7 is most accurate at a throat velocity of 4570 cm/s. At throat velocities and liquid-to-gas ratios typical of commercial units the mean droplet size is estimated with an accuracy ±50 percent. As an alternative, Boll suggests Equation 4.5-8.

$$d_d = \frac{283,000 + 793\left(Q_1/Q_g\right)^{1.922}}{V_g} \qquad \text{(Eq. 4.5-8)}$$

where

d_d = sauter mean droplet size, μm.
V_G = gas velocity in throat, ft/s.
Q_L/Q_G = liquid-to-gas ratio, gal/1000 ft^3.

The impactor parameter takes into account the fundamental variables that influence inertial impaction, namely, aerodynamic particle size and particle-droplet relative velocity. This is parameter calculated from Equation 4.5-9.

$$K_i = \frac{V_R(d_i)^2}{9\mu\ d_d} \qquad \text{(Eq. 4.5-9)}$$

where

K_i = impaction parameter, dimensionless.
d_i = aerodynamic particle diameter i, $cm \times 10^{-4}\ (g/cm^3)^{0.5}$.
μ = gas viscosity at actual temperature, g/s-cm.
d_d = sauter mean droplet size, cm.
V_R = particle-droplet relative velocity, cm/s.

The theoretical penetration curves that can be generated from Equations 4.5-6 to 4.5-9 are shown in Figures 4.5-12 and 4.5-13. These figures illustrate the strong influence of throat velocity and liquid-to-gas ratio in these equations. Results of this approach are conveniently summarized in Figure 4.5-14 for a case with f = 0.25.[3,16]

A comparison of Calvert's model (Equations 4.5-6, 4.5-7, and 4.5-9) and actual scrubber performance data[17] is shown in Figure 4.5-15. The empirical f factor strongly affects the degree in which the model fits a specific scrubber.

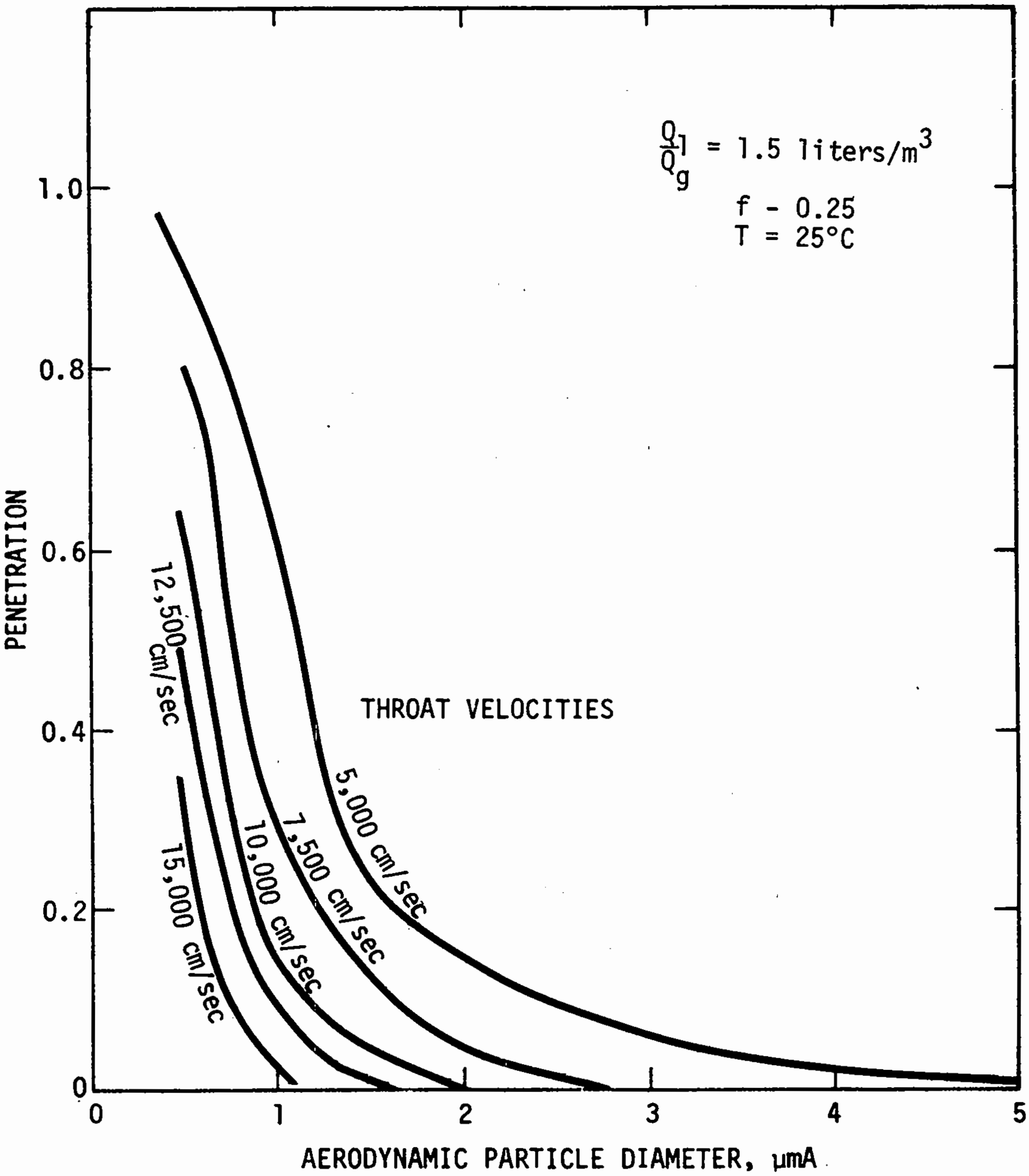


Figure 4.5-12. Theoretical penetration curve for a venturi scrubber illustrating effect of throat velocity.

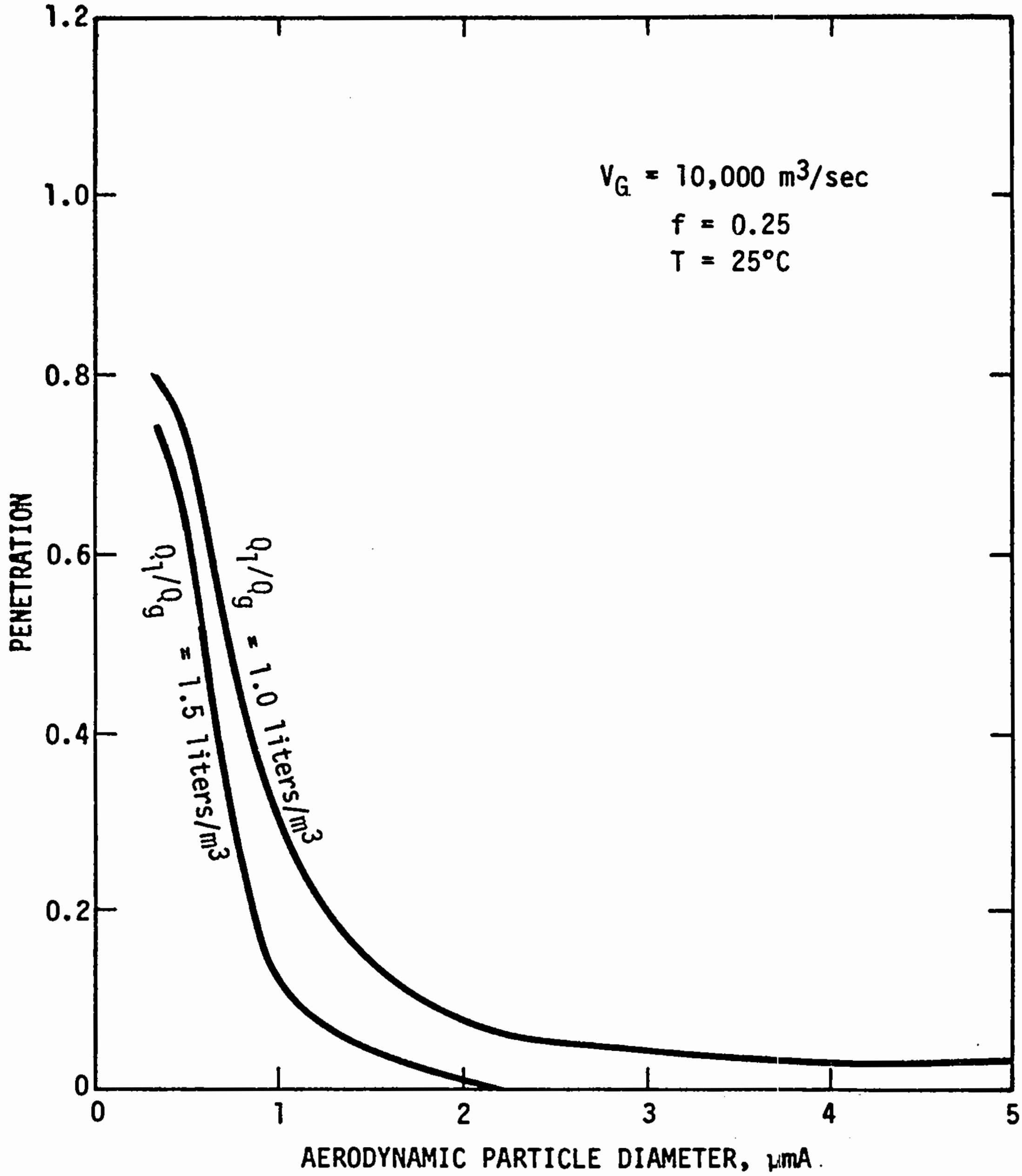


Figure 4.5-13. Theoretical penetration curves for venturi scrubber illustrating effect of liquid-to-gas ratios.

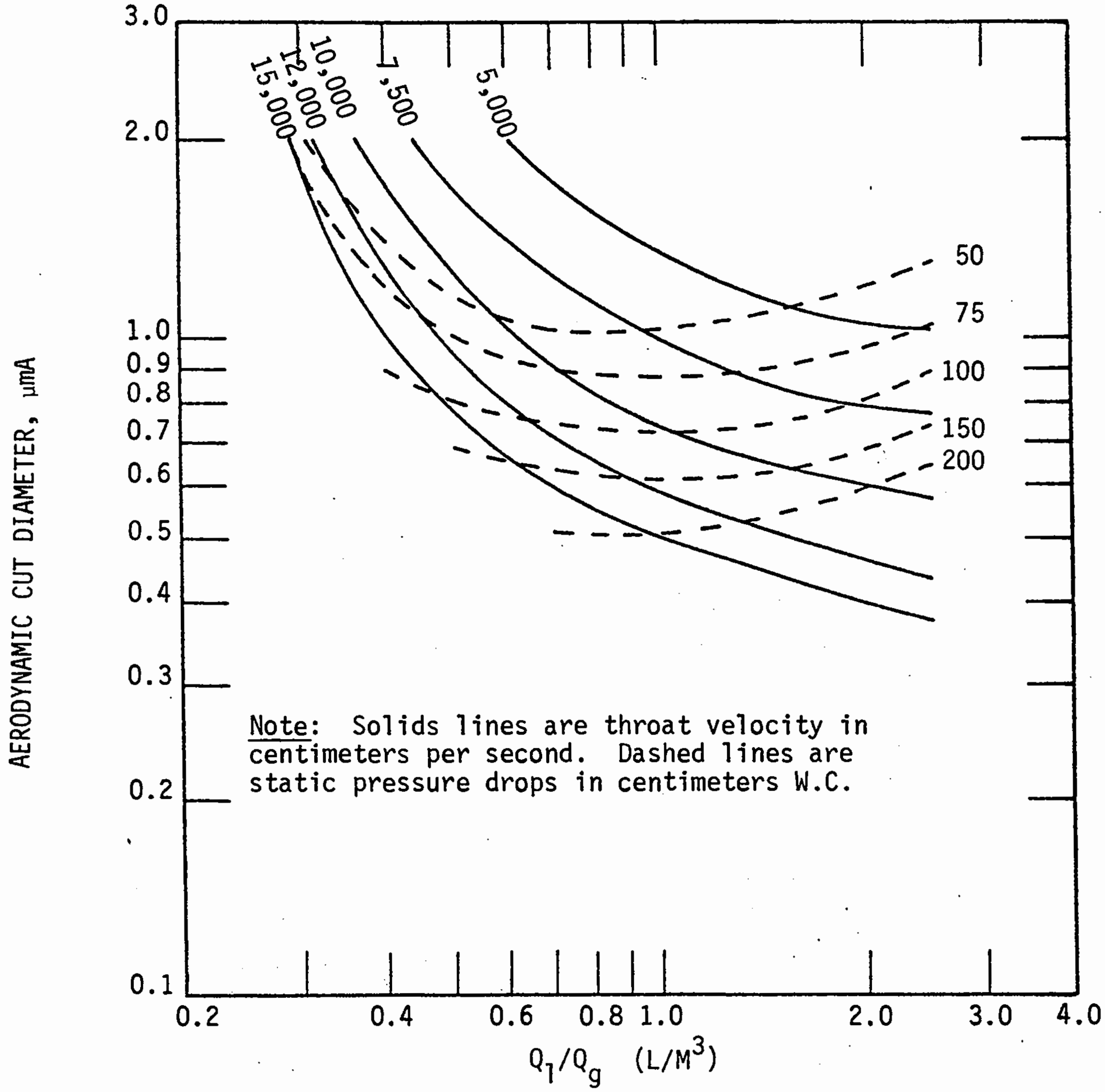


Figure 4.5-14. Predicted venturi scrubber performance for f = 0.25.

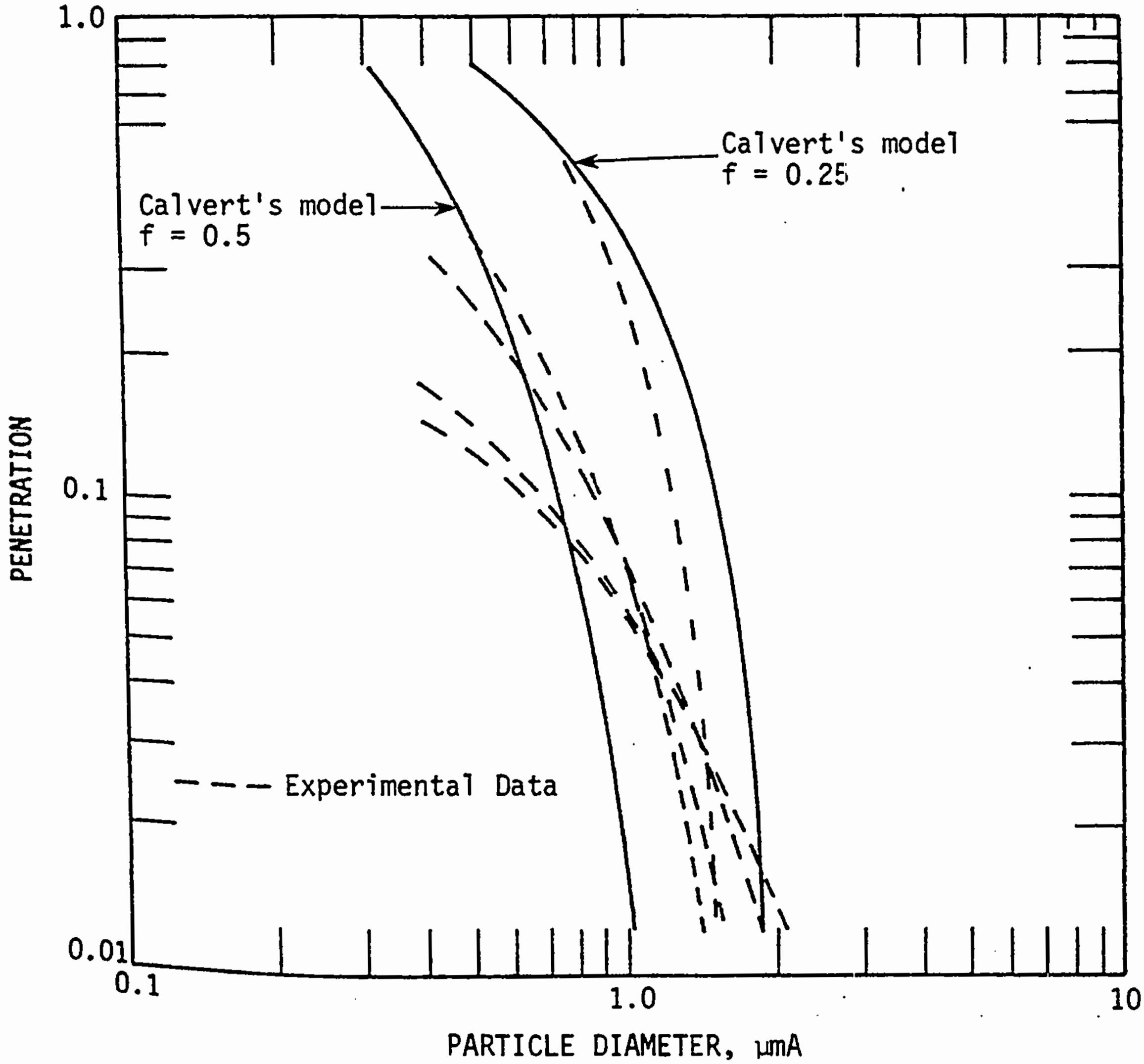


Figure 4.3-15. Comparison of Calvert's Model results against measured penetration data.

Yung, Calvert, and Barbarika[18] have presented a refined model, which incorporates a number of changes from the Calvert model, including elimination of the f parameter. A simplified equation is presented in Equation 4.5-10 for a scrubber in which all particle capture occurs in the throat. It should be noted that the inverse tangent function should be expressed in radians.

$$\frac{\ln Pi}{B} = \frac{1}{K_{po}(1-u^*_{de} + \frac{0.7}{K_{po}})} \left[4K_{po}(1 - u^*_{de})^{1.5} + 4.2\,(1 - u^*_{de})^{0.5} - 5.02\, K_{po}^{0.5} \left((1 - u^*_{de}) + \frac{0.7}{K_{po}} \right) \tan^{-1} \left[\frac{(1-u^*_{de})\, K_{po}}{0.7} \right]^{0.5} \right] - \frac{1}{K_{po} + \frac{0.7}{K_{po}}} \left[4\, K_{po} + 4.2 - 5.02\, K_{po}^{0.5} \left(1 + \frac{0.7}{K_{po}} \right) \tan^{-1} \left[\frac{K_{po}}{0.7} \right]^{0.5} \right]$$

(Eq. 4.5-10)

$$B = \left[\frac{Q_l}{Q_g} \right] \left[\frac{\rho_l}{\rho_g} \right] \left[\frac{1}{C_{DO}} \right]$$

(Eq. 4.5-11)

$$K_{po} = \frac{C\, d_i^{\,2}\, \rho_p u_{Gt}}{9 \mu_g d_d}$$

(Eq. 4.5-12)

$$C_{DO} = 55/N_{Re} \text{ (for } 100 < N_{Re} < 500)$$

(Eq. 4.5-13)

$$u^*_{de} = 2\,[1 - x^2 + (x^4 - x^2)^{0.5}]$$

(Eq. 4.5-14)

$$x = 1 + 0.187 \frac{l_t C_{DO}\ \rho_g}{d_d\ \rho_l}$$

(Eq. 4.5-14)

where

l_t = venturi throat length, cm.

C_{DO} = drop drag coefficient at throat inlet, dimensionless.

p_g = gas density, g/cm³.

p_l = drop density, g/cm³.

d_d = drop diameter, cm.

N_{Re} = drop Reynolds number, dimensionless.

μ_g = gas viscosity, kg/cm-s.

u_{Gt} = gas velocity in throat, cm/s.

Q_l = liquid flow rate, cm³/s.

Q_g = gas flow rate, cm³/s.

u^*_{de} = ratio of liquid drop velocity at throat exit to gas velocity at exit, dimensionless.

C = Cunningham correction factor, dimensionless.

Figure 4.5-16 is a comparison of the Yung et al. model against the same scrubber performance data presented earlier in Figure 4.5-15. The revised model is considered more accurate than the earlier Calvert model, however, it is also much more complex.[18] In another comparison with field units, Calvert, Barbarika and Monahan[17] have concluded that the revised model adequately predicts penetration with the following qualifications.

1. Actual penetration of submicrometer particles is less than predicted.

2. Actual penetration of particles greater than 1 μm is greater than predicted.

3. Accurate measurement of the liquid-to-gas ratio improves the predicted penetration curve.

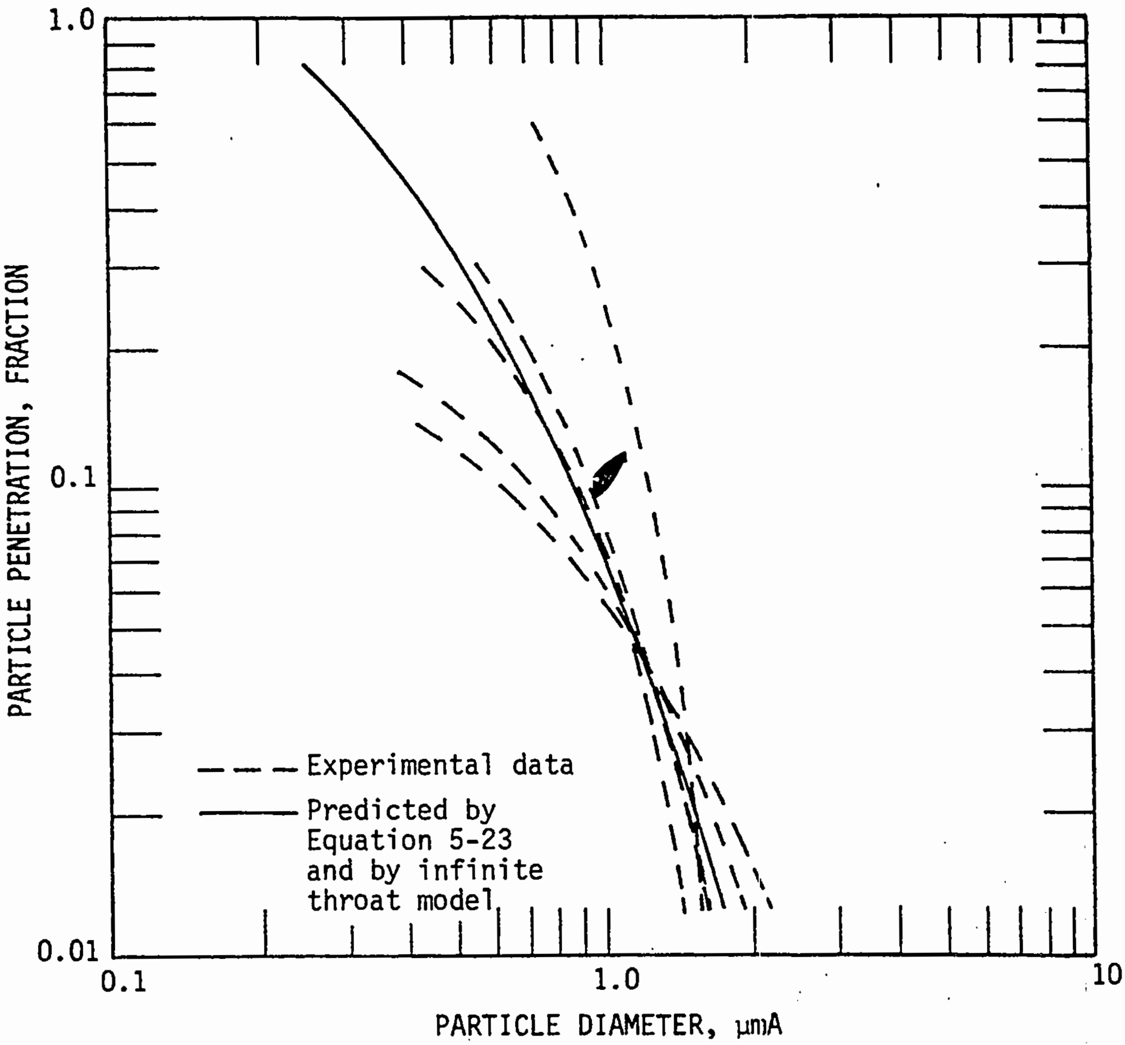


Figure 4.5-16. Comparison of Yung, Calvert, and Barbarika Model against measured penetration data.

Optimization of venturi scrubber design based on modification of Calvert's model[3] has been discussed by Leith and Cooper.[19] Other theoretical approaches for calculating particle collection in venturi scrubbers have been described by Crawford[7] and Strauss.[10]

An empirical approach based on the "contact" power utilized has been described by a number of investigations. The contact power approach is based on the concept that penetration is directly related to the energy input into the gas-liquid contact.[8-13] For gas-atomized scrubbers, the power consumption, P_C, is approximated by Equation 4.5-16.[12]

$$p_G = 0.158\ \Delta P \qquad \text{(Eq. 4.5-16)}$$

where

p_G = power consumed, hp/1000 acfm.

ΔP = gas phase pressure drop, in. W.C.

When the liquid stream adds a significant fraction of the total energy, equations presented in references 12 and 13 may be used. The total energy, P_T, is the sum of the gas- and liquid-phase power consumption.

$$P_T = P_G + P_L \qquad \text{(Eq. 4.5-17)}$$

The scrubber collection efficiency, N_T, is then expressed as shown in Equation 4.5-18.

$$N_T = \alpha P_T^{\gamma} \qquad \text{(Eq. 4.5-18)}$$

where

N_T = number of transfer units $\left(\ln\left(\frac{\text{inlet grain loading}}{\text{outlet grain loading}}\right)\right)$, dimensionless.

P_T = total power consumption, hp/1000 acfm.

α,γ = constants, dimensionless.

The constants are parameters dependent on the characteristics of the particulate matter. Using this approach, one assumes that no independent effects can be attributed to throat velocity, liquid-to-gas ratio, scrubber design and other parameters.

In certain cases good correlations can be achieved using this approach. Figures 4.5-17 and 4.5-18 show the relationship between outlet loadings and static pressure drop (an approach similar to Equation 4.5-18). Hesketh[11]

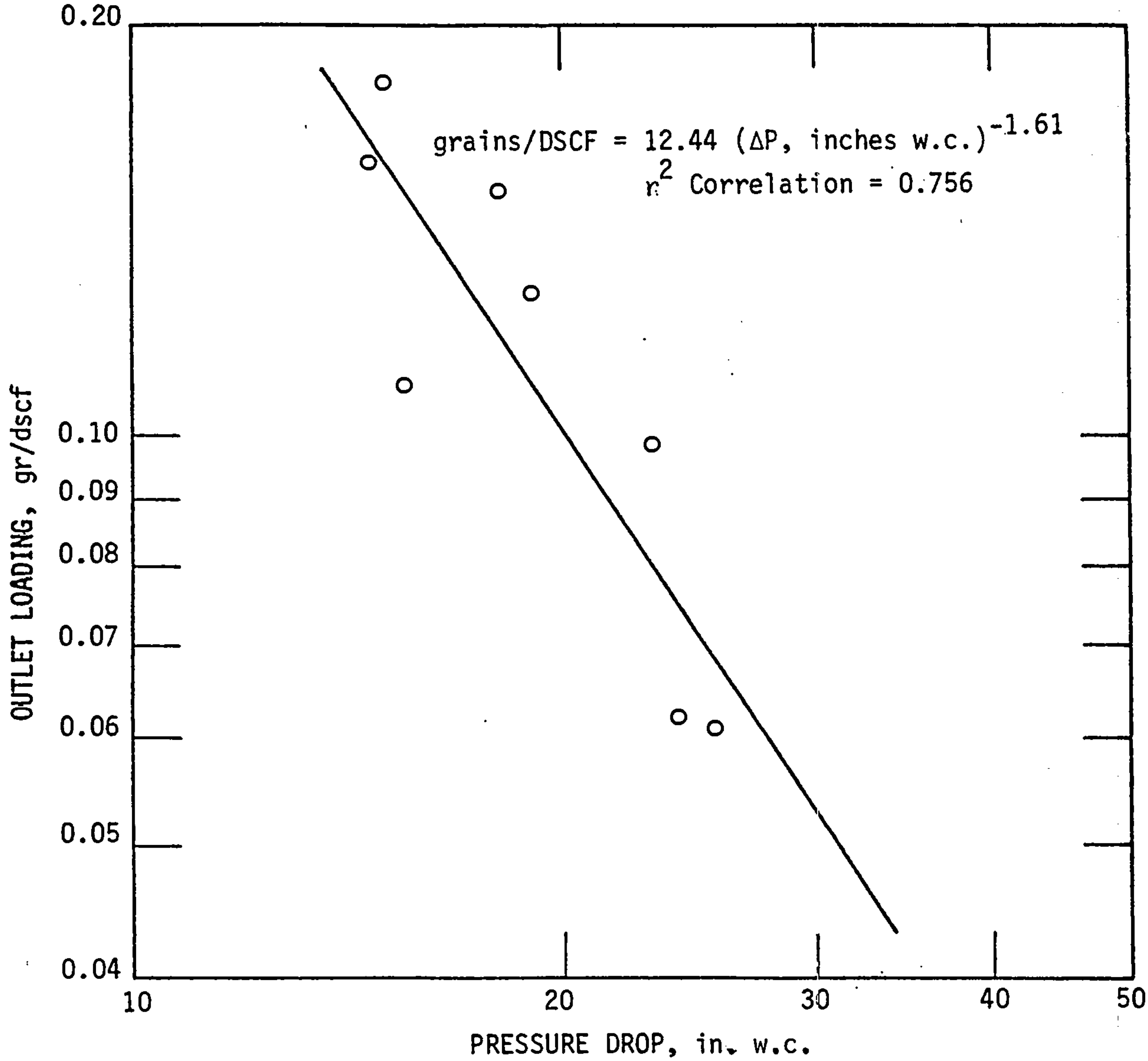


Figure 4.5-17. Comparison of venturi scrubber outlet loadings to static pressure drops for oil-fired lime kilns.

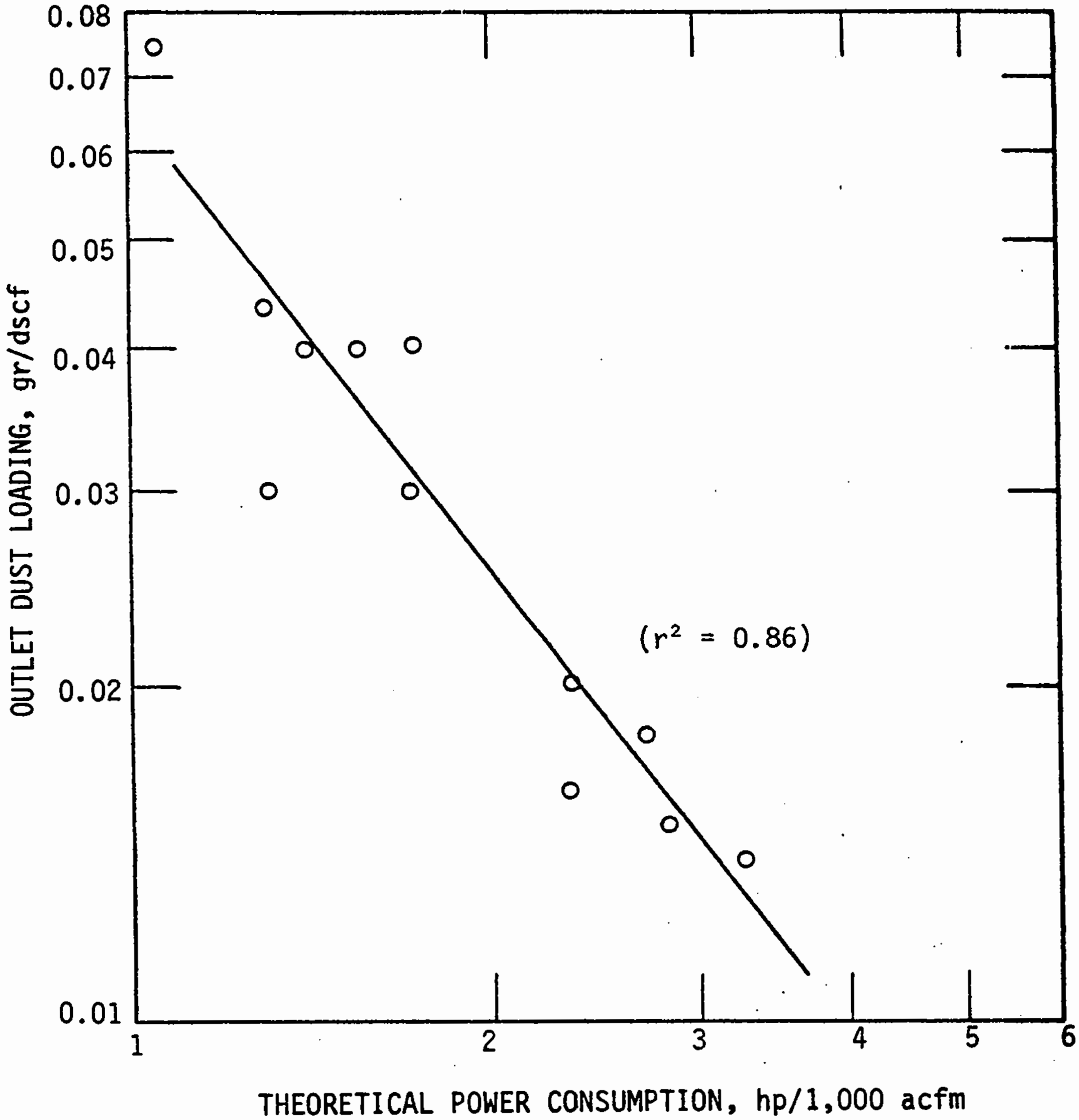


Figure 4.5-18. Correlation of coal-fired boiler scrubber outlet dust loading with theoretical power consumption.[12]

has developed an empirical equation (4.5-19) relating static pressure drop and penetration. As shown in Figure 4.5-19 there is a good relationship between the two.

$$P_t = 3.47\ \Delta P^{-1.43} \qquad \text{(Eq. 4.5-19)}$$

A more complete description of the contact power approach is available in references 8 through 13.

4.5.2.1.5 Other scrubber types. Many other scrubber types are available, for most of which the penetration curves are similar to those presented in this section. Additional information on wet scrubber operating principles is given in References 1, 3, 5, 7, and 10.

4.5.2.2 Static Pressure Drop. Factors affecting the static pressure drop in a wet scrubber include scrubber geometry, gas velocity, and the liquid-to-gas ratio. Typical liquid-to-gas ratios are listed in Table 4.5-2 and typical static pressure drops are listed in Table 4.5-3. Calvert et al.[3] have summarized equations useful for predicting pressure drop in various types of scrubbers. A detailed summary of static pressure drop equations applicable to venturi scrubbers is presented by Yung, Calvert, and Barbarika.[18]

TABLE 4.5-2. TYPICAL LIQUID-TO-GAS RATIOS FOR WET SCRUBBERS

Scrubber type	Liquid-to-gas ratio, liters/m^3
Venturi	0.70 - 1.00
Cyclonic spray tower	0.70 - 1.30
Spray tower	1.30 - 2.70
Moving bed	1.30 - 2.70
Impingement plate	0.40 - 0.70
Packed bed	0.10 - 0.50

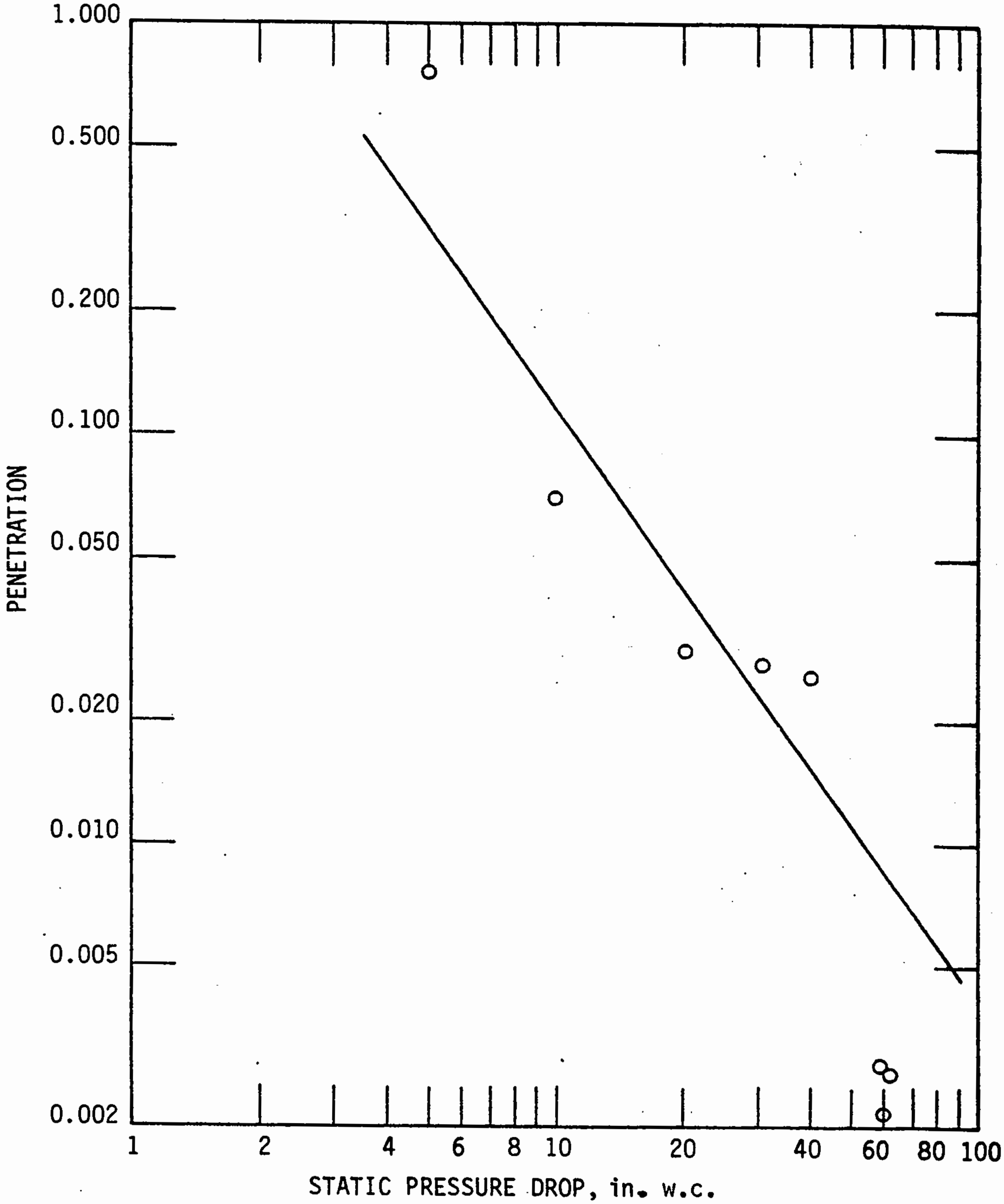


Figure 4.5-19. Comparison of predicted penetration as calculated in Equation 4.5-19 and measured penetration (reprinted by permission from Hesketh, J. Air Poll. Control Assoc. Vol. 24, No. 10, 1974).

TABLE 4.5-3. TYPICAL SCRUBBER PRESSURE DROP

Scrubber type	Pressure drop, kPa
Venturi	1.5 - 18.0
Centrifugal (cyclonic) spray	0.25 - 0.8
Spray tower	0.25 - 0.5
Impingement plate	0.25 - 2.0
Packed bed	0.25 - 2.0
Wet fan	1.0 - 2.0
Self-induced spray (orifice)	0.5 - 4.0
Irrigated filter (filter bed scrubber)	0.05 - 0.8

Calvert et al.[3] presented a simple approach for calculation of venturi static pressure, as shown in Equation 4.5-20.

$$\Delta P = 0.001\ V_t^2 (Q_l/Q_g) \qquad \text{(Eq. 4.5-20)}$$

where

ΔP = static pressure drop, cm. W.C.

V_t = throat velocity, cm/s.

Q_l/Q_g = liquid-to-gas ratio, (cm³/s)/(cm³/s).

Yung et al.[18] have discussed a modified form of this equation as shown in Equation 4.5-22. The parameter u_{de}^* is the same as that described earlier with respect to Equation 4.5-14.

$$\Delta P = 0.001\ u_{de}^*\ V_t\ (Q_l/Q_g) \qquad \text{(Eq. 4.5-21)}$$

Hesketh[11] described an equation including throat area, Equation 4.5-22.

$$\Delta P = (V_t^2 \rho_G A^{0.133} L^{0.78})/1270 \qquad \text{(Eq. 4.5-22)}$$

where

ΔP = static pressure drop, in. w.c.

V_t = throat velocity, ft/s.

ρ_G = gas density, lb/ft³.

A = throat cross-sectional area, ft².

L = liquid-to-gas ratio, gal/1000 acfm.

4.5.3 Design of Particulate Scrubbers

4.5.3.1 Sizing of Wet Scrubbers. The overall dimensions of a scrubber are established to provide the design gas velocity within the various sections of the vessel. Care must be taken to ensure an even gas velocity throughout the mixing and demisting sections. Sharp turns should be avoided in ductwork, and distribution baffles should be used where short-circuiting would otherwise be likely to occur. In general, scrubbers operate at higher average gas velocities than fabric filters or ESP's and therefore are usually more compact.[1]

4.5.3.2 Nozzle Selection and Liquid Distribution. The liquid distribution system in a scrubber is intended to provide even distribution of properly sized liquid droplets for contacting particulate in the mixing zone. For this purpose, nozzles must be selected that will properly atomize the liquid. The two general categories of nozzles use either hydraulic pressure or compressed air to atomize the water. The various types of hydraulic-pressure nozzles produce hollow-cone, solid-cone, or fan-shaped sprays with various spray angles. Two-fluid nozzles use compressed air instead of water pressure as the primary force for atomizing the water. Use of two-fluid nozzles is especially attractive when an extremely small droplet distribution is desired and when fluid viscosity is a problem.

Most nozzles produce a broad spectrum of droplet sizes rather than one distinct size. It is often convenient, however, to express droplet size by a single value such as the average diameter or the Sauter mean diameter (the hypothetical droplet whose ratio of surface area to volume is equal to that of the overall spray). In general, increasing water pressure (or air pressure in two-fluid nozzles) will reduce the average or Sauter mean droplet diameter. The droplet size population may be modified by additives such as propan-1-ol but not necessarily by detergents.[20] Hesketh[21] has reported that the addition of nonionic, low foaming surfactants reduced outlet dust loadings 50 percent by improving particle wettability and/or atomization.

Because many scrubbers are operated with recirculating slurries, the design of nozzles introducing the scrubbing liquid is of critical importance. With some scrubbers (packed towers, gas-atomized units) extensive distribution is needed at the point of liquid entry, but the scrubber elements provide liquid distribution. With other scrubbers the requirements range from a hollow-cone spray to a full-cone spray. The most stringent requirements are for high-pressure sprays that create the small water droplets needed for high efficiency in scrubbers whose primary consumption of energy is in the nozzles (preformed-spray scrubbers).

Nozzle plugging may be a major problem.[22] The area formerly sprayed by a plugged nozzle becomes subject to scaling and heat damage. The critical factor in nozzle design is the minimum internal orifice. As the scrubber size increases, the nozzle size normally increases. Under highly abrasive conditions, ceramic nozzles may be needed. Special care must be taken when installing and removing these nozzles to avoid breakage. Heat can also cause breakage if a proper method of installation is not followed.[23]

4.5.3.3 <u>Presaturators for Hot Gases</u>. The scrubbing of particulate from hot gases presents special problems not associated with gases at ambient temperature. The heat in hot gases can evaporate substantial portions of the scrubbing liquid droplets and adversely affect liquid/ particle contact. In a hot gas stream, some droplets may evaporate before particulate contact and others may evaporate after particulate contact, and thus cause the particulate to be reentrained. Hot gases can also damage scrubber materials, especially fiberglass-reinforced plastics. Presaturation can be economical when cooling of the gases permits the use of less expensive materials of construction in the scrubber and when the lower volume of the cooled gases allows the use of smaller scrubber vessels, fans, dampers, and ducts.[24]

High-temperature gases are usually cooled to near saturation by spray quenching prior to entry into a scrubber. In most scrubber applications approximately 1½ to 2½ times the theoretical evaporation demand is required to quench the gases because of the kinetics of the cooling process.[24] As in the scrubbing process, nozzle design and arrangement are important in quenching. As size of the quench water droplet decreases, the kinetics of the cooling process increases and the evaporation demand becomes closer to theoretical.

Quenching is frequently accomplished with scrubbing liquor rather than clean water. In some applications, however, the use of scrubbing liquor for quenching can reduce scrubber performance. Most recirculating scrubbing liquors contain very high levels of both suspended and dissolved solids. As quench water evaporates, these solids can be reentrained into the gas stream and must be collected again in the scrubber. Dissolved solids in evaporating quench liquor can form fine particulate in the size range that may escape collection in a scrubber.[25] If fine particulate are regenerated in this manner, the net effect is that contaminants are returned to the scrubber inlet gas stream in a form more difficult to collect. It is usually best, therefore, to use the cleanest water available for presaturator of a scrubber. This can be accomplished by adding the makeup water directly to the quench system rather than adding all makeup water to a common sump for the quench and scrubber liquors. Using clean water alone for the quench process is even better.

4.5.3.4 Staging of Scrubbers. When higher collection efficiencies are required than can be obtained in a single scrubber, scrubbers are sometimes staged to improve efficiency. When scrubbers are placed in series, end to end, the penetration of particles of one size through the series is the product of individual penetrations of particles of that size (see Equation 4.5-23). The corresponding pressure drop is the sum of individual pressure drops per stage (see Equation 4.5-24). There is a diminishing overall effectiveness in successive stagings, however, if the individual penetration through a single stage by the finer particulate in a gas stream is considerably higher than the penetration of the coarser particulate. Most of the coarse particulate might be collected in the first stages while each successive stage collects only a small fraction of the remaining fine particulate at a relatively high energy cost. Staging is most common with tray-type scrubbers and packed bed scrubbers and is usually limited to three stages. Staging can also be done with two types of scrubbers, such as a spray-tower precleaner followed by a packed-bed scrubber.

$$P_{i_t} = P_{i_1} \times P_{i_2} \times P_{i_3} \cdots\cdot P_{i_n} \qquad \text{(Eq. 4.5-23)}$$

where

P_{i_t} = total penetration of particles of aerodynamic diameter i

P_{i_1} = penetration of particles of aerodynamic diameter i from stage 1

$$\Delta P_t = \Delta P_1 + \Delta P_2 + \cdots + \Delta P_n \qquad \text{(Eq. 4.5-24)}$$

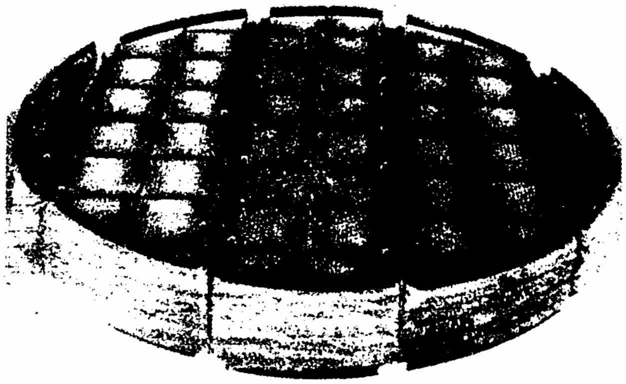
4.5.3.5 Liquid Entrainment Separators. Wet scrubbing of particulate is a two-step process, the second step being separation of the scrubbing liquid droplets from the gas stream. This step is important in the ultimate collection of particulate because poor liquid separation will cause reentrainment of the particulate.

There are four basic types of liquid entrainment separators[26] or "demisters" (Figure 4.5-20). The mesh-pad and chevron types utilize inertial impaction of the liquid droplets to cause their agglomeration and removal. The centrifugal and cyclonic types utilize centrifugal inertia to collect the liquid droplets.

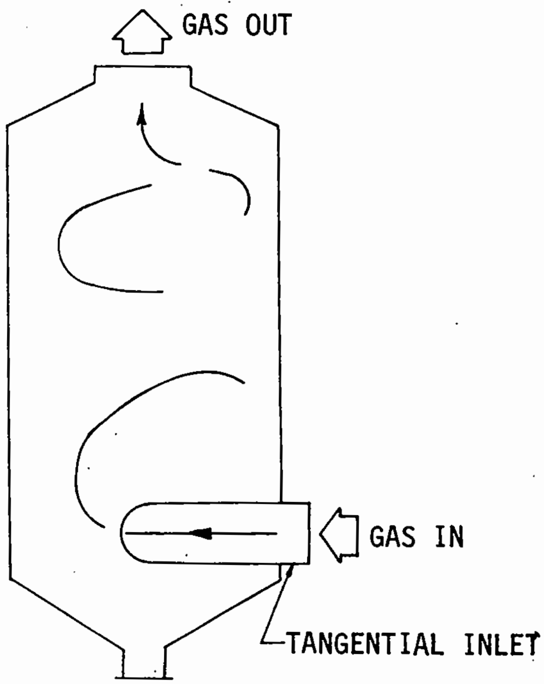
Plugging can be a persistent problem in mesh and chevron mist eliminators in certain applications. Centrifugal-type mist eliminators are less prone to plugging. Plugging can usually be minimized by continuous or intermittent spraying of the mist eliminators.

4.5.3.6 Liquid Handling Facilities. Water usage and waste disposal may become critical factors in the final selection of a wet scrubber. The quantity of particulate collected, the size distribution of the particulate, and the presence of dissolved contaminants in the scrubbing liquid have great bearing on the amount of water and the type of liquid handling facilities needed. Present water quality regulations require that most new scrubber installations and many existing scrubber installations recirculate scrubbing liquors to prevent the contamination of surface waters with the collected air contaminants (Section 6). Recirculation, however, tends to concentrate the dissolved scrubbing liquor contaminants.

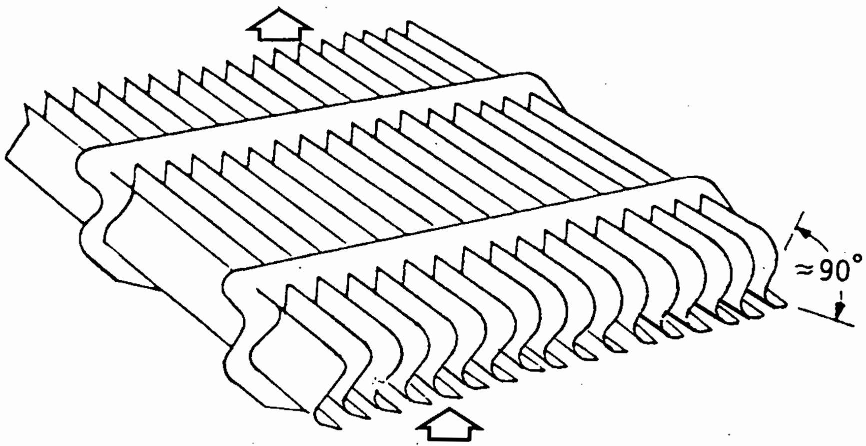
Liquid handling facilities in recirculating scrubber systems usually include a slurry pump; a makeup water pump; a settling basin or pond; and associated piping, valves, and spray nozzles. It is sometimes necessary to construct multiple settling basins or to install clarifiers with drag chains or rotary sludge collectors to settle and remove suspended solids from scrubbing liquors. Additional procedures for liquid handling can include filtration; chemical treatment, for example to control pH level and aid flocculation; and many other treatments common to industrial wastewater treatment facilities (Section 6).



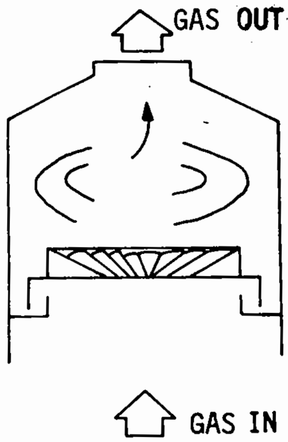
MESH TYPE MIST ELIMINATOR
(Courtesy of Koch Engineering
Company, Inc.)



CENTRIFUGAL MIST COLLECTOR[6]



CHEVRON MIST ELIMINATOR[10]



CYCLONIC MIST
COLLECTOR[6]

Figure 4.5-20. Liquid entrainment separators (courtesy of Industrial Gas Cleaning Institute, Inc.).

Because scrubbing slurries are often corrosive and abrasive, all liquor handling pumps, piping, nozzles, and valves must be constructed of resistant materials or be lined with suitable protective materials. Since slurries can also cause plugging, it is advantageous to install cleanout traps and service hatches in many components. In some systems reliability can be ensured only by installing duplicate pumps.

4.5.3.7 Materials of Construction. Materials of construction for scrubber applications must be carefully selected to withstand corrosive and abrasive agents in the gases or liquors, and to withstand any high temperatures that may occur. If the process conditions are properly defined before design begins, the experienced scrubber manufacturer can design a scrubber that will withstand its service environment. Many scrubbers, however, fail because inappropriate materials are selected after a superficial investigation of process conditions, or because insufficiently resistant materials are substituted to reduce costs.[27]

Investigation of each scrubber application should include chemical analysis of the raw materials, combustion products, and scrubbing liquids. The operating histories of any scrubber installations in similar applications should also be reviewed. Finally, review of the literature about materials performance is recommended; and when materials performance data are not available, in situ coupon tests may be required. After all relevant information has been compiled, the designer prepares a list of materials suitable for the expected service. Selection of materials of construction from this list of candidates will be based in part on the relative costs.

Although the above mentioned procedures should be followed in selection of materials, some general aspects of materials applications can be mentioned. Table 4.5-4 lists the major types of metals available for scrubbers and ancilliary components, together with their major properties, general corrosion behavior, and relative costs. Not listed are the nonmetallic materials such as fiberglass-reinforced plastic, ceramics, protective coatings, and wood, which are appropriate in many scrubber applications.

4.5.3.8 Instrumentation. Proper instrumentation is vital to the monitoring of scrubber performance. Many installations require instrumentation with associated alarms and interlocks to protect valuable components

TABLE 4.5-4. PROPERTIES OF METALS USED AS MATERIALS OF CONSTRUCTION FOR WET SCRUBBERS AND AUXILIARY COMPONENTS[28 30]

Metal	Properties/uses	Corrosion resistance
Cast iron	High strength; low ductility; brittleness; hardness; low cost	Ordinary cast irons exhibit fair resistance to mildly corrosive environments; high-silicon cast irons exhibit excellent resistance in a variety of environments (hydrofluoric acid is an important exception); cast irons are susceptible to galvanic corrosion when coupled to copper alloys or stainless steels
Carbon steel	Good strength, ductility, and workability; low cost	Fair to poor in many environments; low pH and/or high dissolved solids in moist or immersion service leads to corrosion; properly applied protective coatings give appropriate protection in many applications; susceptible to galvanic corrosion when coupled to copper alloys or stainless steels
Martensitic stainless steel (410, 416, 420, 440c)	Chromium alloy, hardenable by heat treatment; typically used for machine parts; costs 2 to 5 times more than carbon steel	Good
Ferritic stainless steel	Chromium alloy, not hardenable by heat treatment; costs 2 to 4 times more than carbon steel	Good; better than martensitic stainless steels; resists stress corrosion; better chloride resistance than austenitic stainless steels
405	Modified for weldability	
430	General-purpose, often used for chimney liners	Good resistance to atmospheric corrosion
442,446	Used in high-temperature service	

(continued)

TABLE 4.5-4 (continued)

Metal	Properties/uses	Corrosion resistance
Austenitic stainless steel	Chromium and nickel alloy; not hardenable by heat; hardenable by cold working; nonmagnetic	Excellent; better than martensitic or ferritic stainless steel (except for halides)
	Types 201, 202, 301, 302, 303, 304, and 304L cost 3 to 5 times more than carbon steel; types 310, 316, 316L, and 321 cost 4 to 10 times more than carbon steel	
201, 202	Nitrogen added, used as a substitute for 301 and 302	
301	Good hardenability	
302	General-purpose	
304	General-purpose	
304L	Modified for weldability	
310	Used in high-temperature service	
316	Used in corrosive environments	Superior corrosion resistance; good acid resistance; resistant to hot organic acids; good pitting resistance
316L	Improved weldability	
Nickel alloy	Good strength; costs over 10 times more than carbon steel	Excellent resistance in most environments; not resisant in strong oxidizing solutions such as ammonium and HNO_3
Inconel[a]		Good resistance to stress corrosion
Monel[a]		Good resistance to hydrofluoric acid
Hastelloy[b] and Chlorimet[c]		Excellent overall resistance
Titanium	High strength; light weight (60% that of steel); costs over 10 times more than carbon steel	Exceptional resistance at ambient temperatures Excellent resistance at other temperatures, except that crevice corrosion is possible in chloride solutions above 250°F

[a]Registered trademark of Huntington Alloys, Inc.

[b]Registered trademark of the Stalite Division of Cabot Corporation.

[c]Registered trademark of the Duriron Company, Inc.

from malfunctions such as loss of water pressure or a process temperature runaway.

Every major scrubber system should include a meter to measure static pressure drop across the scrubber and a meter to indicate water flow through the scrubber. Static pressure drop can be measured with a differential pressure gauge or manometer. Care must be taken in the design of the tubing and fittings to prevent plugging and to allow easy cleaning, and tubing materials should be selected to withstand the service expected. For example, certain plastics can melt when exposed to high temperatures, some plastics become excessively brittle at low temperatures, and polypropylene tubing is degraded under continuous exposure to sunlight. Water flow rates can be measured by in-line flow meters or doppler type indirect flow meters. A less expensive and less accurate method of flow measurement is the use of a pump pressure gauge calibrated to indicate flow rates. Open-channel type flow-measuring devices such as the Parshall flume are sometimes useful, although the preferred measuring point for liquor flow is between the pump outlet and the scrubber spray nozzles.

For sources that generate hot gases, the gas temperatures must be monitored if the scrubber contains materials that cannot withstand high temperatures. A high-temperature alarm and/or an interlock system is usually installed to shut down the process or to bypass the scrubber system. Alarm systems can also be included to indicate low water levels in orifice-type scrubbers. In systems that include presaturators, water flow through the scrubber and the presaturator should be measured individually. Where gas temperatures vary widely, it is sometimes necessary to install temperature feedback instrumentation that controls the water flow rates to the presaturator.

Scrubber instrumentation often includes liquor pH indicators, fan ammeters, and fan vibration sensors. The pH meters are needed when pH of the scrubbing liquor must be closely controlled. Maintaining clean, accurately calibrated probes, although often difficult, is essential to the success of pH control. Fan ammeters and tachometers can be used in conjunction with the manufacturer's fan performance curves to provide an estimate of gas flow through the scrubber system, or these instruments can be used to provide a quick comparison of the system's performance with previous performance. It is helpful in all scrubber systems to provide small ports in the ducting before and after the fans, the scrubber vessels, and the presaturators to allow pitot velocity traverses, gas temperature measurements, and static pressure measurements.

4.5.4 Operation and Maintenance of Particulate Scrubbers

4.5.4.1 Common Malfunctions. Wet scrubbers can provide continuous, reliable service when they are operated properly and maintained regularly. Poor operation and maintenance leads to component failure. Most scrubber failures result from abrasion, corrosion, solids buildup, and wear of rotating parts. Common failure modes for individual components are discussed below.

4.5.4.1.1 Nozzle plugging. Nozzle plugging is one of the most common malfunctions in scrubbers.[22] Plugged nozzles reduce the liquid-to-gas ratio or cause maldistribution of the liquid. Nozzle plugging results from improper nozzle selection, excessive solids in scrubbing liquors, poor pump operation, and poor sump design. Remedies for nozzle plugging include replacement with nozzles of a different type, frequent cleaning, and reduction of liquor solids content by increasing liquor blowdown and makeup water rates. Because presaturator nozzles are especially prone to plugging, the quench water should be limited to fresh water or very dilute liquors. Many quench nozzles cannot tolerate greater than 2 percent solids in the liquid.[23] Nozzle plugging can be detected by observing the liquid spray pattern the nozzles produce. If the nozzles are not accessible while the pumps are operating, they should be checked during scrubber shutdowns for evidence of caking over the nozzle openings. A decrease in water flow rate during scrubber operation is an additional symptom of nozzle plugging.

4.5.4.1.2 Solids buildup. Solids buildup is another problem common to wet scrubbers and one that is often difficult to control. The two types of solids buildup are sedimentation and chemical scaling. Sedimentation occurs when a layer of particles becomes attached to a surface or settles in areas of low turbulence. Sedimentation can lead to plugging of pipes and ducts or buildup on internal parts. Chemical scaling results from a chemical reaction of two or more species to form a precipitate on the surfaces of scrubber components.

Solids buildup may occur in piping, sumps, scrubber packing, instrumentation lines, or ductwork, and may lead to reduced scrubber efficiency and major equipment failure. Most scrubbers using open pipes cannot reliably tolerate liquor slurries of over 15 percent solids by weight. It is usually best to maintain solids content at less than 6 to 8 percent.[23] Techniques to control scaling include increasing the liquid-to-gas ratio, controlling pH, providing greater residence time in the holding tank, and adding other chemical agents such as dispersants. Solids buildup can be detected by inspection of accessible components and by inspection of the inner surfaces of piping, tubing, and ductwork at removable fittings and hatches.

4.5.4.1.3 Corrosion. Corrosion problems arise frequently in wet scrubbers, especially when the gases being cleaned contain acid-forming compounds or soluble electrolytic compounds. The combustion of fossil fuels, especially coal, coke, and residual fuel oil, yields oxides of sulfur, which can produce sulfuric acid in scrubbing liquors. Metals-refining processes, such as copper and lead smelting, can also produce oxides of sulfur. Combustion of polyvinyl chloride plastics, commonly found in incinerator feedstock, can produce hydrochloric acid in scrubbing liquors. Rotary aggregate dryers and similar process equipment can produce chlorides or fluorides, depending on the composition of the aggregate. The phosphate fertilizer industry and the feldspar industry are especially troublesome sources of fluorides. Acids and electrolytes in general are corrosive to mild steels, chlorides are corrosive to many stainless steels, and fluorides are harmful to nearly all stainless steels except certain specially formulated (and expensive) high-nickel alloys.[28] Recirculation of scrubbing liquors greatly increases the concentrations of any corrosive agents they contain.

Prevention of corrosion is best handled through proper choice of materials of construction and through pH control. When a pH control system is to be the principal defense against corrosion, regular maintenance at frequent intervals is necessary, especially at the pH electrodes. Another common operating problem occurs when scrubber liquor blowdown rates are reduced to limit the emission of pollutants into surface waters. Reducing or eliminating blowdown can so greatly increase the acid and electrolyte concentrations in the liquor that otherwise acceptable materials of construction become ineffective against corrosion.

4.5.4.1.4 Abrasion. Abrasion can occur where gases or scrubbing liquors containing high concentrations of abrasive particulate are in the turbulent mode or are subjected to a sudden change in flow direction. Typical wear areas in scrubbing systems include venturi throats, walls of centrifugal mist collectors near the inlet duct, and elbows in the ductwork.[23] Solutions to abrasion wear include the use of precleaning devices and the use of large-radius turns in ductwork.

4.5.4.1.5 Wear of rotating equipment. Rotating equipment including fans, pumps, and clarifiers must receive special attention in scrubber service because of potential abrasion, plugging, and corrosion. Key wear areas in these components include the bearings and any components rotating in the fluid stream.[31]

Fan wear is a common problem. Forced-draft fans often suffer abrasion because of exposure to particulate-laden gases. Wear problems in forced-draft fans can be addressed by the use of special wear-resistant alloys, by reduction of fan rotation speeds (by installing a larger fan), or by moving of the fan to an induced-draft location on the clean air side of the scrubber system. Induced-draft fans can undergo corrosion or solids buildup on the blades if mist is carried over from the liquid entrainment separator. Induced-draft fan problems can be addressed by use of corrosion-resistant materials or by improving liquid entrainment separation.

Pump wear is also a common problem in scrubber systems. Pump housings, impellers, and seals are subject to abrasion and corrosion by scrubber slurries. Rubber linings and special-alloy pump materials are often used to reduce abrasion and corrosion of the housings or impellers. Installation of a water flush in the seals can help reduce wear of the seals.[31]

4.5.4.2 Preventive Maintenance. Preventive maintenance is an important tool in assuring the continuous operation of scrubber systems. Preventive maintenance programs for scrubbers should include periodic inspection of equipment, replacement of worn parts, periodic cleaning of components prone to plugging, maintenance of an adequate spare parts inventory, and recording of all maintenance performed on scrubber equipment.

All instrumentation such as differential pressure gauges, scrubbing liquor flow meters, pump pressure gauges, and fan ammeters should be observed at least once per work shift. All equipment should be inspected regularly at regular intervals, determined by the severity of service and the likelihood of component failure. Failure-prone items include nozzles and pumps handling slurries, forced-draft fans handling particulate-laden gases, induced-draft fans downstream of inadequate liquid entrainment separators, wear plates, pH probes, and bearings. These items should be inspected as often as once per shift depending on the likelihood of failure. Such components as ductwork and induced-draft fans handling clean, dry gases should be inspected monthly.

All worn parts and malfunctioning equipment should be serviced as they are discovered to prevent deterioration of system performance and to prevent damage to equipment. An inventory of spare parts must be maintained in stock for replacement of nozzles, bearings, pump seals, liners for pumps with replaceable liners, pump impellers, wear plates for fans wheels with wear plates, pH probes, and valve parts.[30] Records should be made of all maintenance performed and all parts replaced. This information is useful in planning subsequent preventive maintenance schedules and in determining the type and number of replacement parts needed.

REFERENCES

1. Theodore, L. and A. J. Buonicore, Industrial Air Pollution Control Equipment for Particulates. CRC Press, Cleveland. 1976.

2. Vincent, E. Wet Collection Devices. In: Air Pollution Engineering Manual. U.S. Environmental Protection Agency Publication No. AP-40, May 1973. pp. 99-106.

3. Calvert, S., J. Goldshmid, D. Leith, and D. Mehta. Wet Scrubber System Study, Volume I: Scrubber Handbook. U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. EPA-R2-72-118a, August 1972.

4. Sargent, G. D. Dust Collection Equipment, Chemical Engineering. January 27, 1969. pp. 130-150.

5. Licht, W. Air Pollution Control Engineering. Marcel Dekker, Inc. New York. 1980.

6. The McIlvane Company. The Wet Scrubber Handbook. Northbrook, Illinois. 1974.

7. Crawford, M. Air Pollution Control Theory. McGraw Hill Book Company. New York. 1976.

8. Semrau, K. T., C. L. Witham, and W. W. Kerlin. Energy Utilization by Wet Scrubbers. U.S. Environmental Protection Agency, Cincinnati, Ohio. Publication No. EPA-600/2-77-234, November 1977.

9. Semrau, K. T. and C. L. Witham. Wet Scrubber Liquid Utilization. U.S. Environmental Protection Agency, Cincinnati, Ohio. Publication No. EPA-650/2-74-108, October 1974.

10. Strauss, W. Industrial Gas Cleaning, 2nd Edition. Pergamon Press, Inc. New York, N.Y. 1975.

11. Hesketh, H. Fine Particle Collection Efficiency Related to Pressure Drop, Scrubbant and Particle Properties, and Contact Mechanism. J. Air Pollution Control Association. 24: 939-942. October 1974.

12. Ranade, M. B. and E. R. Kashdan. Design Guidelines for an Optimum Scrubber System. Second Symposium on the Transfer and Utilization of Particulate Control Technology. U.S. Environmental Protection Agency, Cincinnati, Ohio. Publication No. EPA-600/9-80-039a, September 1980, pp. 538-560.

13. Engineering Science, Inc. Scrubber Emissions Correlation Final Report to U.S. Environmental Protection Agency. Contract No. 68-01-4146, Task Order 49. May 1979.

14. Calvert, S., N. Jhaveri, and S. Yung. Fine Particle Scrubber Performance Tests, U.S. Environmental Protection Agency, EPA-650/2-74-093, October 1974.

15. Boll, R. H., L. R. Flais, P. W. Maurer, and W. L. Thompson. Mean Drop Size in a Full Scale Venturi Scrubber via Transmissometer. J. of Air Pollution Control Association. 24: 934-938. October 1974.

16. Calvert, S., N. C. Jhaveri, and S. Yung. Fine Particle Scrubber Performance Tests. U.S. Environmental Protection Agency Publication No. EPA-650/2-74-093, October 1974.

17. Calvert, S., H. F. Barbarika, and G. M. Monahan. Evaluation of Three Industrial Particulate Scrubbers, U.S. Environmental Protection Agency, Cincinnati, Ohio. Publication No. EPA-600/2-78-032, February 1978.

18. Yung, S., S. Calvert, and H. Barbarika. Venturi Scrubber Performance Model, U.S. Environmental Protection Agency, Cincinnati, Ohio. Publication No. EPA-600/2-77-172, August 1977.

19. Leith, D. and D. W. Cooper. Venturi Scrubber Optimization. Atmospheric Environment. Volume 14, 1980. pp. 657-664.

20. Atkinson, D. S. F. and W. Strauss. Droplet Size and Surface Tension in Venturi Scrubbers. J. Air Pollution Control Association. 28: 1114-18. November 1978. pp. 1114-1118.

21. Hesketh, H. Atomization and Cloud Behavior in Wet Scrubbers. Presented at the Symposium in Control of Fine Particulate Emissions from Industrial Sources. San Francisco, California. January 15-18, 1974. pp. 455-478.

22. National Asphalt Pavement Association. The Maintenance and Operation of Exhaust Systems in the Hot Mix Batch Plant. Information Series 52, Second Edition. February 1978.

23. Schifftner, K. C. Venturi Scrubber Operation and Maintenance. Presented at the U.S. EPA Environmental Research Information Center Seminar on Operation and Maintenance of Air Pollution Equipment for Particulate Control, Atlanta, Georgia. April 1979.

24. Industrial Gas Cleaning Institute, Inc. Scrubber System Major Auxiliaries. Publication WS-4. Stamford, Connecticut. 1975.

25. Kalika, P. W. How Water Recirculation and Steam Plumes Influence Scrubber Design. Chemical Engineering. July 28, 1969. pp. 133-138.

26. Industrial Gas Cleaning Institute, Inc. Basic Types of Wet Scrubbers. Publication No. WS-3. Stamford, Connecticut. June 1976.

27. Mappes, T. and R. D. Tems. An Investigation of Corrosion in Particulate Control Equipment. U.S. Environmental Protection Agency, Research Triangle Park, N.C. Publication No. 340/1-81-002. February 1981.

28. Nation Association of Corrosion Engineers. NACE Basic Corrosion Course. Houston, Texas. May 1977.

29. Benzer, W. C. Steels. Chemical Engineering 77(22). October 12, 1970.

30. Fontana, M. G. and N. D. Greene. Corrosion Engineering. McGraw Hill. New York, N.Y. 1967.

31. Czuchra, P. A. Operation and Maintenance of a Particulate Scrubber System's Ancillary Components. Presented at the U.S. EPA Environmental Research Information Center Seminar on Operation and Maintenance of Air Pollution Equipment for Particulate Control. Atlanta, Georgia. April 1979.

4.6 INCINERATORS

Incinerators are seldom, if ever, used solely to remove particulate matter because they tend to be more expensive and more energy intensive than alternative control techniques. Applications are restricted to sources of combustible matter with low gas flow rates and low particulate concentrations. Principal among these are curing ovens, textile coating, charcoal manufacturing, food processing, and certain chemical processes. The particulate-laden gas stream from these sources normally contains other pollutants, such as volatile organic compounds (VOC), carbon monoxide, and odorous compounds. Particulate control in the incinerator may in fact be only ancillary to the control of malodors or VOC. Information concerning use of incinerators for gaseous pollutant control is available in Reference 1.

An incinerator vaporizes and oxidizes particles. It is the only particulate control system that does not concentrate the particulate matter for subsequent disposal.

4.6.1 <u>Types of Incinerators</u>

Three basic types of incinerators are used for particulate matter removal: direct, thermal, and catalytic. Because the catalytic type is prone to severe operating problems with particulate-laden gas streams, its use is limited.

4.6.1.1 <u>Direct and Thermal Combustion</u>. These two basic designs are similar and rely on simple combustion without the aid of a catalyst to oxidize organics, essentially to water and carbon dioxide. The basic difference between the two types is that in direct combustion the gas stream contains organic gases or vapors in sufficient concentration to sustain combustion most or all of the time; in thermal combustion the gas streams are lean, usually well below the lower explosive limit (LEL) for the particular organic gas or vapor. Thus thermal incinerators require appreciable auxiliary fuel to achieve effective combustion, whereas direct afterburners often require only a pilot flame to initiate combustion and to sustain combustion during periods when the gas stream is lean. Many direct incinerators are open flares. Where thermal incinerators are used, the gas stream usually contains enough oxygen to burn the organic contaminants. Gas streams vented to direct incinerators are often too rich in organics (concentrations are above the Upper Explosive Limit), and air must be introduced to initiate combustion. A typical thermal incinerator is illustrated in Figure 4.6-1.

4.6.1.2 Catalytic Combustion. This type of incinerator uses catalysts to initiate and promote oxidation at temperatures well below those required for thermal incinerators. The combustibles-laden gas stream is preheated and passed through a catalyst bed to oxidize vapor phase organics, predominantly to carbon dioxide and water vapor.

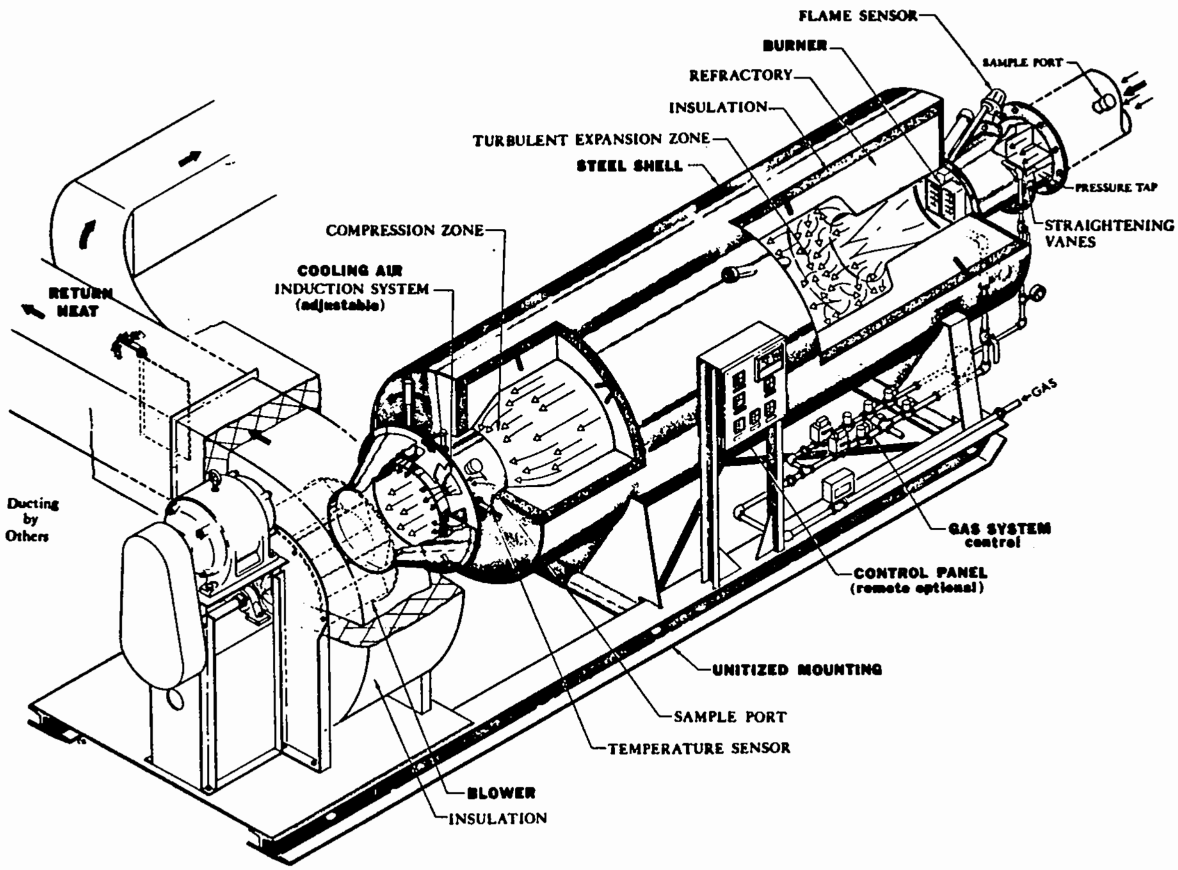
The combustible contaminant concentration must be below the lower explosive limit. Commonly, catalysts are metals of the platinum family and exist as a thin coating on an inert support material. Catalytic combustion is not normally recommended for organic particulate removal because the surface of the catalyst can become coated with particulate matter and thereby inhibit the oxidation reaction. This type of incinerator is not discussed further.

4.6.2 Operating Principles of Incinerators

Combustion involves many complex, interrelated reaction mechanisms between the fuel, fuel decomposition intermediates, and oxygen. Depending on reaction conditions, results can include partially oxidized species such as carbon monoxide, aldehydes, and organic acids, or simply carbon dioxide and water vapor. The latter occurs only when the combustion processes approach completion.

As with any combustion process, the basic variables for particulate matter incineration are reaction temperature, reaction time, and reactant mixing (turbulence). For solid particles, the reaction zone is confined to the surface. At low temperatures the combustion rate is limited by the chemical reaction rate, whereas at higher temperatures the chemical reaction rate is so rapid that the rate of air supply to the surface controls the combustion rate.[2,3]

Combustion of liquid droplets and volatile solids occurs away from the surface of the particle, and combustion rate may be dependent on the rate of heat transfer to the surface, which causes evaporation and thermal decomposition of the solid. Combustion is influenced by the gas velocity, the rate of mixing, and the supply of oxygen.[4,5]



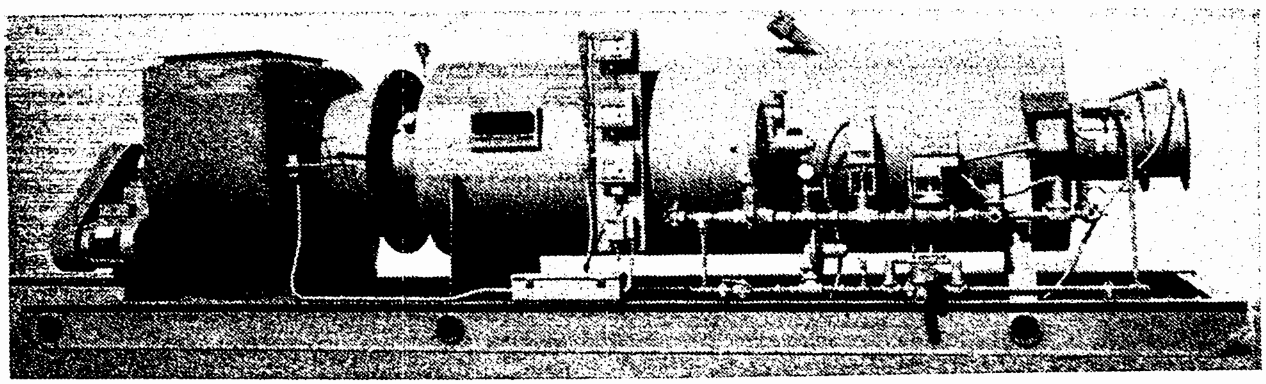


Figure 4.6-1. Typical thermal incinerator.

The temperature in the combustion zone surrounding the particulate matter may exceed the temperature at the interior of the particle and in the surrounding gas by several hundred degrees. Heat transfer is largely by radiation from the incandescent surface of the particle, or from the incandescent carbon formed as an intermediate step in the combustion process.[6]

4.6.2.1 Reaction Temperature. The principal requirement regarding temperature is that the auto-ignition temperature of all species being burned must be exceeded by approximately 100° to 200°C. This allows for a margin of error to account for nonideal combustion conditions, heat losses, and unknown particle composition. Operation at less than the auto-ignition temperature means that combustion reactions are not initiated. Instead, the particles are simply being heated, with possibly some volatilization. Emissions at the stack may not exhibit any noticeable opacity; however, downwind the vapors may recondense as secondary particulate matter. The auto-ignition temperatures of selected organic compounds are presented in Table 4.6-1.[7]

The reaction temperature also influences the rate of the combustion reactions. Most direct flame burners operate in the 650° to 820°C temperature range to obtain maximum combustion within the limits of flame contact, mixing, and residence time in the furnace.[8]

Figure 4.6-2 illustrates the effect of air velocity and particle diameter on the combustion rate of carbon.[9,10,11] The effects of particle size, reaction temperature, combustion gas composition, and gas velocity on the combustion rate of carbon, coal, and several other compounds have been investigated.[2-5,12-14]

4.6.2.2 Reaction Time. Preheat (induction) and combustion times will dictate the overall residence time of the particulate matter in the incinerator. The residence time requirement will determine both combustion chamber dimensions and particle penetration.

The time required to heat the waste gas to peak furnace temperature is dependent on the burner combustion intensity and inlet gas temperature. Values of combustion intensity will vary from 400 kJ per cubic meter per second for low-pressure gas jet mixers to 20,000 kJ per cubic meter per second for premix mechanical burners. A typical value is 5600 kJ per cubic meter per second for premix high-pressure gas jet multiple-port burners.

TABLE 4.6-1. AUTO-IGNITION TEMPERATURES OF ORGANIC COMPOUNDS

Organic compounds	Auto-ignition temperature, oK
Acetone	810
Ammonia	920
Benzene	850
Butadiene	720
Butyl alcohol	640
Carbon disulfide	400
Carbon monoxide	920
Chlorobenzene	950
Cresol	830
Cyclohexane	540
Dibutyl phthalate	680
Ethyl ether	460
Methyl ether	620
Ethane	305
Ethyl acetate	760
Ethyl alcohol	700
Ethyl benzene	740
Ethyl chloride	790
Ethylene dichloride	690
Ethylene glycol	690
Ethylene oxide	700
Furfural	670
Furfural alcohol	760
Glycerin	670
Hydrogen	850
Hydrogen cyanide	810
Hydrogen sulfide	535
Kerosene	530
Maleic anhydride	750
Methane	810
Methyl alcohol	745
Dichloromethane	910
Methyl ethyl ketone	310
Mineral spirits	520
Petroleum naphtha	520
Nitrobenzene	770
Oleic acid	635
Phenol	990
Phthalic anhydride	860
Propane	780
Propylene	780
Styrene	760
Sulfur	505
Toluene	825
Turpentine	525
Vinyl acetate	700
Xylene	770

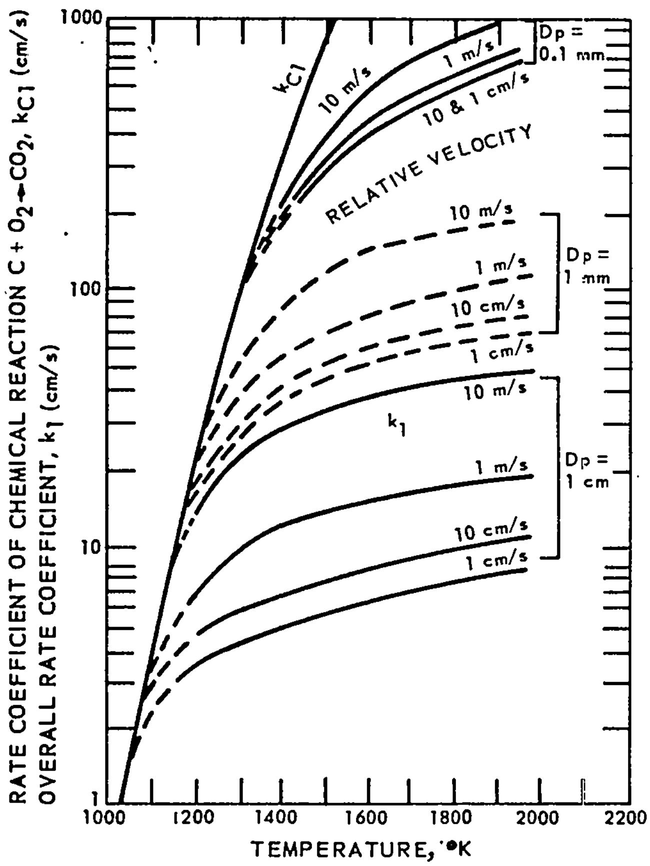


Figure 4.6-2. Effect of air velocity and particle diameter on the combusiton rate of carbon. (D_p = particle diameter).

Combustion time required is dependent on particle size, oxygen content of the furnace atmosphere, furnace temperature, particle composition, gas velocity, and mixing of combustibles. Combustion times for several different materials have been determined and correlated on the basis of the following equations:[15]

$$t_d = (\rho R' T_m d_{po})\ (96\ \phi\ D\ p_g) \qquad \text{(Eq. 4.6-1)}$$

$$t_c = (\rho d_{po})\ (2K_s p_g) \qquad \text{(Eq. 4.6-2)}$$

where

t_d = diffusion-controlled combustion time, sec

t_c = chemical reaction rate-controlled combustion time, sec

ρ = density of carbon residue or coke, g/cm^3

R' = universal gas law constant, 82.06 atm cm^3/mole/K

T_m = mean temperature of stagnant gas film, K

x_o = original diameter of particle, cm

ϕ = combustion mechanism = 1 for CO and 2 for CO_2 formation

D = diffusion coefficient of oxygen at temperature T_m, gm/cm^2

p_g = partial pressure of oxygen in combustion air, atm

K_s = surface reation rate coefficient, g/cm^2 sec atm.

K_s may be calculated by Equation 4.6-3 for soot and by Equation 4.6-4 for coke and carbon residue.

$$K_s = (1.085 \times 10^4 T_s^{-\frac{1}{2}})(e^{-39,300/RT_s}) \qquad \text{(Eq. 4.6-3)}$$

$$K_s = 8710\ e^{-35,700/RT_s} \qquad \text{(Eq. 4.6-4)}$$

where

T_s = surface temperature.

Equation 4.6-1 holds at high temperature, zero gas velocity, and large particle sizes. The equation can be corrected for the effects of gas velocity and turbulence by use of the dimensionless Nusselt conventional heat transfer relationship for spherical particles:[16]

$$N_{Nu} = 2 + 0.68 \, [N_{Pr}^{\;1/3} \times N_{Re}^{\;1/2}] \qquad \text{(Eq. 4.6-5)}$$

where

N_{Nu} = Nusselt Number

N_{Pr} = Prandtl Number, a function of the physical properties of the gas

N_{Re} = Particle Reynolds Number, a function of the physical properties of the gas, particle diameter, and gas velocity.

The Nusselt Number $N_{Nu} = h\,(d_p/k) = 2$ at zero gas velocity, where h = convectional heat transfer coefficient (cal/cm² °C sec); d_p = particle diameter (cm). The inverse function, h, of the stagnant gas film thickness, $d_p/2$, surrounding the particle and directly proportional to the thermal conductivity of the furnace atmosphere, k (cal/cm² °C cm sec).

The film thickness decreases with increasing velocity and decreasing particle size to such an extent that the combustion rate for particles smaller than 100 micrometers is limited only by chemical kinetics at normal incinerator temperatures.

Equation 4.6-1 is of limited value in design because particles larger than 100 micrometers are easily collected by other gas cleaning devices and would require excessive retention time and furnace volume.

Equation 4.6-2 holds for particle sizes smaller than 100 micrometers and for temperatures at which the combustion rate is determined by chemical kinetics.

Total combustion time for a carbon residue-forming particle then becomes:

$$t_r = t_i + t_d \cdot K_v + t_c \qquad \text{(Eq. 4.6-6)}$$

where

t_r = total residence time, sec

t_i = induction time, sec

K_v = volatile matter correction factor determined by the equation:

$$K_v = (1 + E/100)/(1 + E/100 - V/100) \qquad \text{(Eq. 4.6-7)}$$

where

E = percent excess air

V = percent volatile matter

The combustion time for hydrocarbon liquid droplets larger than 30 micrometers at zero gas velocity may be computed using the following equation:[11]

$$t_d = 29{,}800/p_g \quad M_w \, T^{-1.75} \quad d_{po}^{2} \qquad \text{(Eq. 4.6-8)}$$

where

M_w = molecular weight

T = furnace temperature, K.

The combustion time of particles smaller than 30 micrometers is dependent on the combustion rate of the hydrocarbon vapors.

The time required to burn a 5 x 10^{-6} cm soot particle of 2 grams/cubic centimeter density in a furnace atmosphere containing 0.20 atmosphere of oxygen at 1260°C can be computed using the Equations 4.6-2 and 4.6-3. The time required would be 0.51 second.

Total residence time in the furnace, including heat-up time from 100°C, would be induction time + combustion time = total time, or:

$$t_r = 0.208 + 0.510 = 0.718 \text{ second}$$

In practice, minimum gas furnace retention time is about 0.30 second at a temperature of 920°C. Particle retention time may be increased by designing the combustion chamber in the shape of a cyclone with a small tangential inlet, and by introducing the gases at a high velocity.

4.6.2.3 Heat Transfer. The transfer of heat from burner flame to gaseous and particulate matter is an important factor in determining the furnace size, operating temperatures, and fuel requirements of direct flame contact incinerators. Heat transfer is best achieved by mixing when gases are burned, and best achieved by radiant heat transfer when particulate matter is burned.[16,17]

For purposes of burning particulate matter, radiant heat transfer and furnace temperature uniformity may be increased by increasing the emissivity of the burner flame. This can be accomplished by limiting the air supply to produce a sooty flame, by using high carbon-to-hydrogen ratio (C/H) fuels, by adding soot, or by using fuel oil (by carburetion).

4.6.3 Design of Incinerators

Factors that must be considered in incinerator design for particle-containing gaseous waste include fuel requirements, burner selection, protection systems, heat recovery, refractory type, and instrumentation. Design methodologies must take into account the complex interdependencies of operating parameters and the highly variable characteristics of many sources. Semi-empirical approaches based on previous experience with analogous sources are generally used.[7]

4.6.3.1 Fuel Requirements. Fuel requirements and burner capacity may be determined by means of a heat balance, using the heat of combustion of the fuel and the sensible heat needed to raise the temperature of the waste gas and the products of combustion up to the desired combustion temperature. The heating value of the contaminant must be deducted to determine net fuel requirements.[8,18-20]

Insurance underwriters ususally limit the heating value of the waste gas stream to combustible vapor concentrations of less than one-fourth of the lower explosive limit. For organics this is equivalent to about 480 kJ per standard cubic meter. The combustible particulate matter normally contributes only a negligible heating value because of the low grain loadings.

Figure 4.6-3 presents the energy requirements for a thermal incinerator at various influent gas stream coloric loads. Similar curves applicable to a given facility could be generated by use of the procedures described in Reference 2.

Energy requirements are inversely proportional to the influent gas temperature--the higher the temperature, the less the sensible heat that must be added to raise the influent gas stream to combustion temperature.

4.6.3.2 Heat Recovery. Energy requirements may be substantially reduced by use of heat recovery equipment. The additional capital and maintenance cost must be weighed against the energy savings.

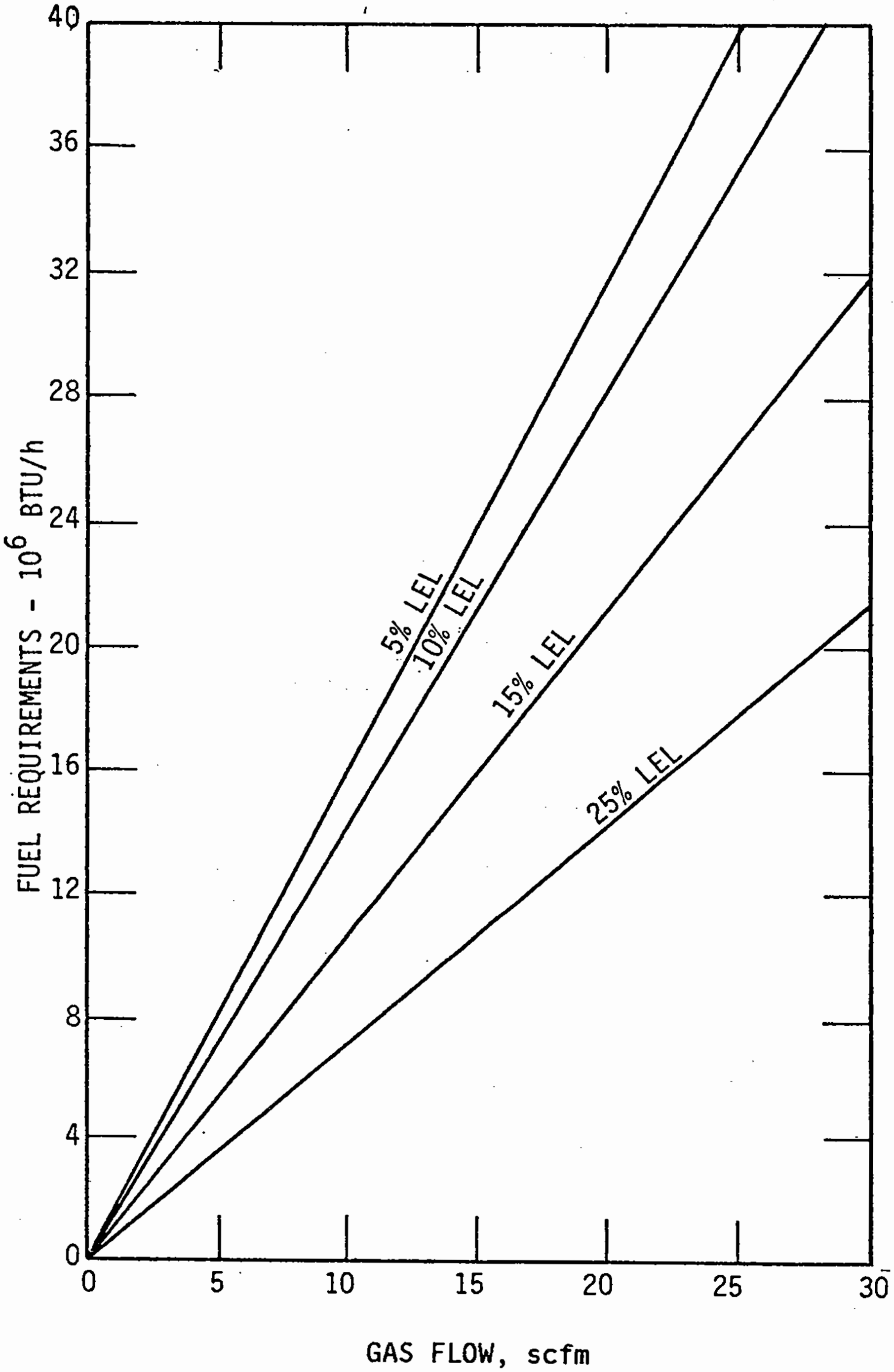


Figure 4.6-3. Fuel required to oxidize different concentrations of combustible vapor (heat content of combustible particulate assurance negligible).

Heat recovery equipment used to recover heat from the flue gas may be grouped into two classifications: recuperative and regenerative. Recuperative heat exchangers, which recover heat on a continuous basis, include crosscurrent-flow, countercurrent-flow, and cocurrent-flow heat exchangers. For a given heat flow and temperature drop, heat exchanger surface requirements will be the least in the countercurrent-flow heat exchanger. The crosscurrent-flow, U-shaped recuperator shown in Figure 4.6-4 is obviously subject to fouling if combustion effectiveness decreases to the point that large particles remain in the effluent. Cold-side deposits may also occur.

Cocurrent-flow heat exchangers are often used where a moderate level of heat recovery is required. The cost of countercurrent-flow heat exchanger construction may be greater than that for cocurrent-flow because operation at lower temperatures (near the dewpoint) may require use of special alloys or alloy steels.

Regenerative heat exchangers recover heat by intermittent heat exchange through alternate heating and cooling of a solid. Heat flows alternately into and out of the same exchanger as air and flue gas flows are periodically reversed. Regenerative heat exchangers are of fixed- and moving-bed types.

A fixed-bed, pebble-stove, regenerative afterburner is shown in Figure 4.6-5. When gas is passed through the pair of pebble-type regenerators connected back to back, the gas is heated on the upstream side and cooled on the downstream side. When the upstream bed and gas temperature drop, gas flow is reversed and the heat transfer process is repeated. Particulate matter is effectively retained and incinerated. Heat recovery efficiencies in excess of 95 percent can be achieved.[21]

A commonly used rotary regenerative heat exchanger consists of a partitioned rotating cylinder containing a heat sink and heat transfer surface area. The cylinder is partitioned along its axis by appropriate gas seals, so that hot flue gas and cold waste gas may be passed through the heat exchanger on opposite sides of the cylinder. Heat is absorbed from the hot flue gas by the heat exchanger surface and transferred by the continuous rotation of the heat exchange surface to the cold waste gas side, where the heat is absorbed by the incoming cold gases. Heat recovery efficiency ranges from 85 to 95 percent.[21]

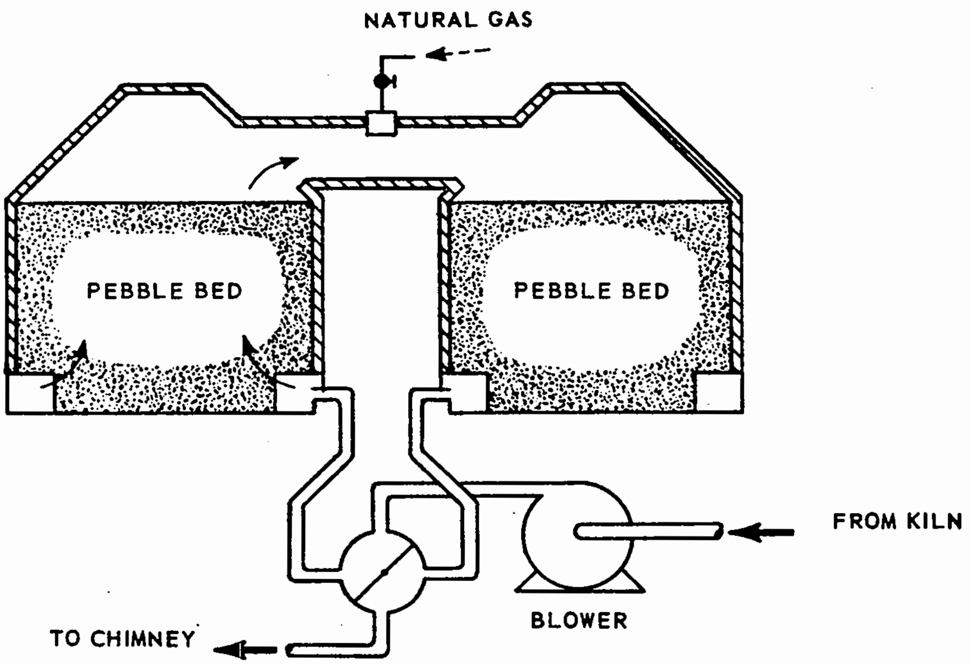


Figure 4.6-5. Fixed-bed, pebble-stone, regenerative afterburner.

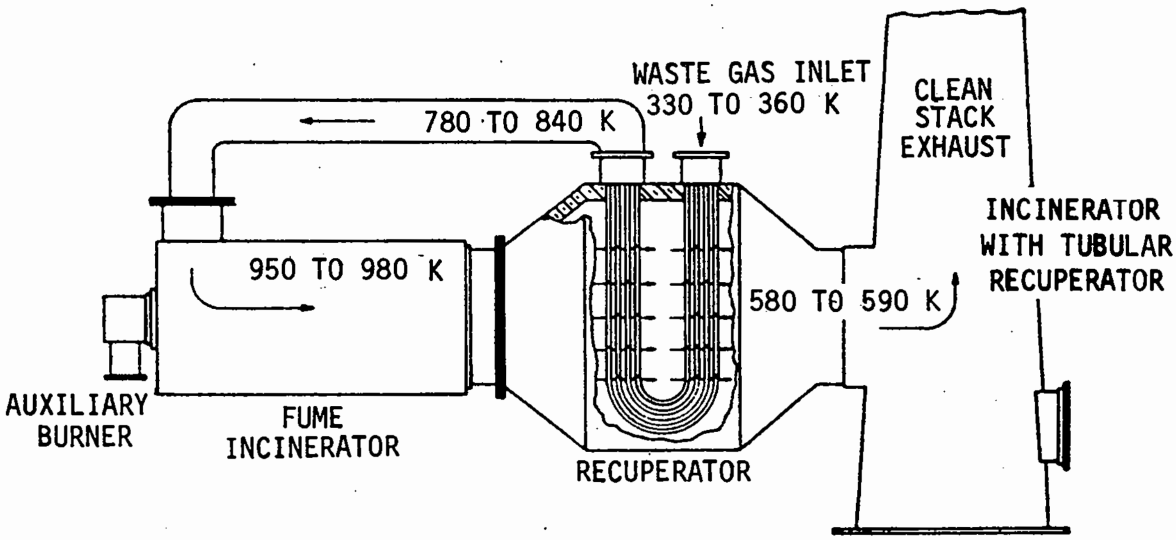


Figure 4.6-4. Tubular recuperator.

4.6.3.3 Hood and Ducts. Furnace inlet gases and vapors from paint and varnish cooking kettles and other sources must be maintained at temperatures above condensation to avoid exhaust duct fouling. Collection ductwork is usually insulated and may be heated by means of an external duct that serves to recover heat from the flue gas, which reduces fuel requirements.

Duct gas velocities are usually high, ranging from 1000 to 1700 m/min, to prevent the settling of particulate matter, to effect a high heat recovery rate between the flue gas and furnace feed gas, and to minimize the danger of flashback and fire hazards.[7,22,23]

Other safety devices for minimizing fire hazards may include diluting vapors to below the lower explosive limits, using flame arrestors, and including a wet scrubber between the direct flame combustor and the vapor source. Dilution of the vapors may be accomplished by recirculation of a portion of the flue gas, which would substantially reduce fuel requirements.

Flame arrestors may consist of a packed bed of pebbles, metal tower packing, aluminum rings (Figure 4.6-6), or corrugated metal gridwork (Figure 4.6-7), in conjunction with a blast gate or other pressure-release device. Flashback through the bed is prevented by bed gas velocities, by pressure drop, and by cooling the flame to below combustion temperatures.[24,25]

Other types of flame arrestors include spray chambers, wet seals, and dip legs. Wet flame arrestors have the disadvantage of cooling and humidifying the exhaust gas with a consequent increase in fuel requirements. Wet sprays are capable of partial removal of the solids.

Flame arrestors, regardless of type, should not be relied upon as the primary defense against explosions.[7] The combustibles content of the gas stream should be continuously kept at less than 25 percent of the lower explosive limits, with consideration given to known fluctuations in process operation.

4.6.3.4 Burners. The burner, the key operational component of an incinerator system, is based on the type of service and capacity required.

Three major types of gas burners are available:[7] raw gas burners, premix gas burners, and forced-draft gas burners. The raw gas burner relies on an induced draft of air to mix combustion air with the gas. This burner consists of a cluster or ring of holes for the raw gas generation jets. The premix burner is fed an already proportioned fuel/air mixture, which is

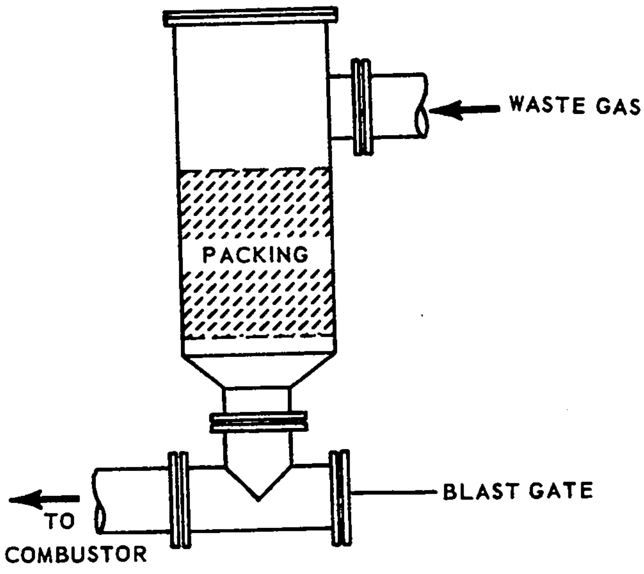


Figure 4.6-6. Packed-bed flame arrestor.

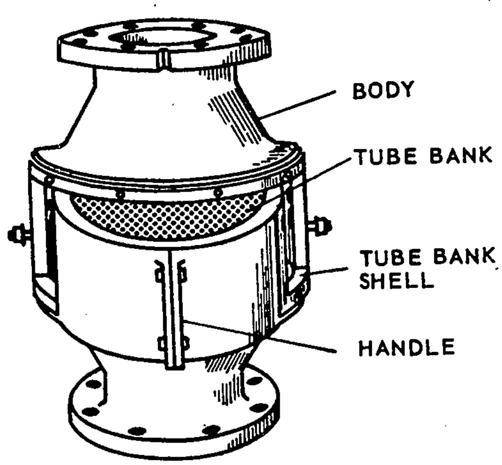


Figure 4.6-7. Corrugated metal flame arrestor with cone removed and tube bank pulled partly off the body.

ignited at the burner orifice or ring. Obviously, care must be taken to avoid flashback. The forced-draft burner involves separate delivery of fuel and combustion air to the burner. After mixing, the air and gas are ignited by a pilot.

Oil burners are similar to the raw gas and forced-draft gas burners. The principal difference is the addition of an oil atomizing system to ensure intimate mixing of the fuel with air. A typical forced-draft oil burner is shown in Figure 4.6-8. In this model, compressed air is used to atomize the oil. The combustion air could be either contaminated effluent or ambient air.

4.6.3.5 <u>Construction Materials</u>. Incinerator surfaces that will be exposed to high temperatures and erosive or corrosive conditions must be constructed of alloys capable of withstanding high temperatures or must be lined with refractory materials.

4.6.3.6 <u>Metals</u>. Underwriters Laboratories, Inc., limits temperatures at which alloy steels are used to approximately 100°C below the temperature at which scale formation occurs. Martensitic and ferritic stainless steels are recommended for use in areas that are exposed to wide ranges of temperature and to corrosive conditions.[26] Temperature limitations for other metals and alloys are determined by design stress and safety requirements.[20]

4.6.3.7 <u>Refractories</u>. Refractories used in direct-flame incinerators increase radiant heat transfer, act as a support structure, and are resistant to abrasion and corrosion. They also must be capable of withstanding thermal shock. Fire clay refractories are commonly used in incinerator construction because of low cost, spall resistance, and long service life. Fire clay refractory bricks are classified (Table 4.6-2) into maximum service classes according to American Society for Testing and Materials (ASTM) standards.[27] Their softening points, as determined by pyrometric cone equivalent (PCE), help determine their maximum service class.[28] Other requirements include limits on shrinkage, spalling loss, and deformation under load. Commonly used castable fire clay refractories (Table 4.6-3) are of two ASTM classes.[29]

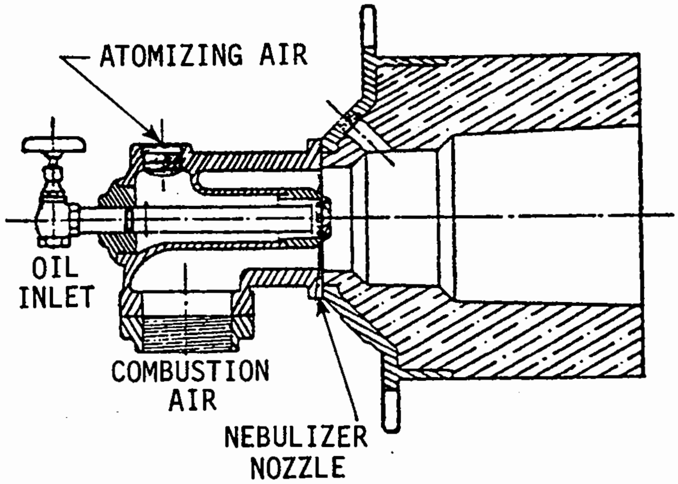


Figure 4.6-8. Typical forced draft oil burner.

TABLE 4.6-2. ASTM CLASSIFICATION OF FIRE CLAY REFRACTORIES

Refractory type	PCE	Temperature, °C
Low heat duty	19	1520
Intermediate heat duty	29	1640
High heat duty	21-32	1680-1700
Super heat duty	33	1745

TABLE 4.6-3. COMMONLY USED CASTABLE FIRE CLAY REFRACTORIES

ASTM No.	Temperature, °C	Density, kg/m^3	Special properties
24	1310	4.5-5.3	Insulating, light-weight
27	1480	6.9-7.8	General-purpose

Service temperature ranges of various refractories for corrosive conditions are shown in Figure 4.6-9 and in Table 4.6-4. The literature contains further information.[27,28]

4.6.3.8 Instrumentation. Minimum instrumentation for an incinerator system consists of a temperature indicator that enables an operator to determine if gas temperature is too low for effective oxidation of particulate matter or too high for the materials of construction.

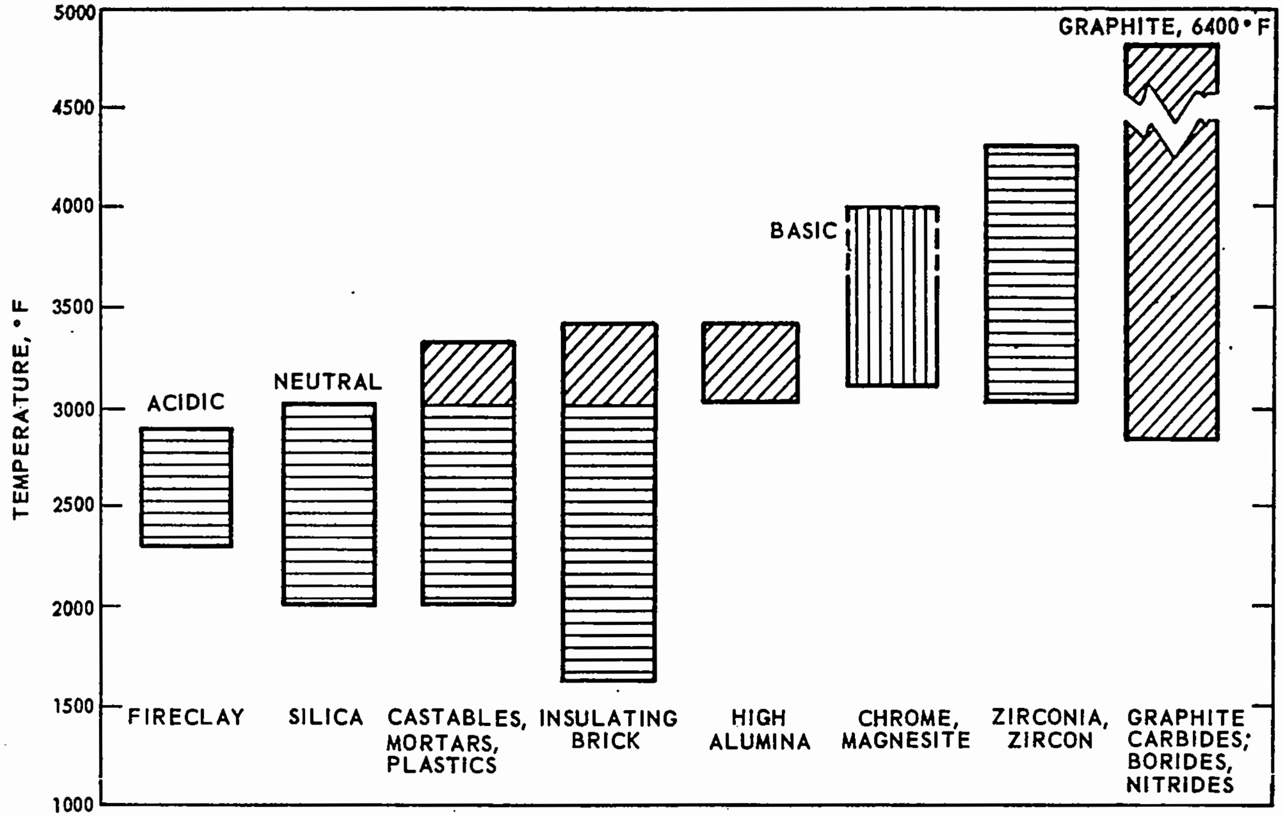


Figure 4.6-9. Service temperature ranges for refractories.
(Courtesy of McGraw-Hill Book Co.)

TABLE 4.6-4. GENERAL PHYSICAL AND CHEMICAL CHARACTERISTICS OF CLASSES OF REFRACTORY BRICK

Type of brick	Typical chemical composition	Approx. bulk density, kg/m3	Fusion point, oC	Chemical nature	Deformation under hot loading	Apparent porosity %	Permeability	Hot strength	Thermal shock resistance	Chemical resistance: to acid	Chemical resistance: to alkali
Silica	SiO_2 95%	7.23	1950	Acid	Excellent	21	High	Excellent	Poor[a]	Good	Good at low temperatures.
High-duty fireclay	SiO_2 54% Al_2O_3 40%	8.42	1718	Acid	Fair	18	Moderate	Fair	Fair	Good	Good at low temperatures.
Super-duty fire-clay	SiO_2 52% Al_2O_3 42%	8.80	1743	Acid	Good	15	High	Fair	Good	Good	Good at low temperatures.
Acid-resistant (type H).	SiO_2 59% Al_2O_3 34%	8.92	1670	Acid	Poor	7	Low	Poor	Good	Insoluble in acids except HF and boiling phosphoric.	Very resistant in moderate concentrations.
Insulating brick	Varies	1.89-4.71	Varies		Poor	65-85	High	Poor	Excellent	Poor	Poor
High-alumina	Al_2O_3 50-85%	10.69	1760 1870	Slightly acid	Good	20	Low	Good	Good		
Extra-high alumina	Al_2O_3 90-99%	11.62 9.62	1650 2010	Neutral	Excellent	23	Low	Excellent	Good	Good except for HF and aqua regia.	Very slight attack with hot solutions.
Mullite	Al_2O_3 71%	9.62	1810	Slightly acid.	Excellent	20	Low	Good	Good	Insoluble in most acids.	Slight reaction
Chrome-fired	Chrome ore 100%	12.25	Varies	Neutral	Fair	20	Low	Good	Poor	Fair to good	Poor
Magnesite-chrome bonded.[b]		11.44			Good	12	Very low.	Good	Excellent		
Magnesite-chrome fired.	MgO 50-80% CR_2O_3 5-18% Fe_2O_3 3-13% Al_2O_3 6-11%	11.31	Varies	Basic	Excellent	20	High	Good	Excellent	Fair except to strong acids.	Fair resistance low temperatures.
Magnesite-chrome high-fired.	SiO_2 1.2-5%	11.31			Excellent	18	High	Excellent	Excellent		
Magnesite-bonded[b]		11.31			Good	11	Low	Good	Good	Soluble in most acids.	Good resistance low temperatures.
Magnesite-fired	MgO 95%	11.18	2150	Basic	Good	19	Moderate	Good	Good		
Zircon	ZrO_2 67% SiO_2 33%	12.57	1950	Acid	Excellent	25	Very low	Excellent	Good	Very slight	Very slight
Zirconia (stablized).	ZrO_2 94% CaO 4%	15.40	2650	Slightly acid	Excellent	23	Low	Excellent	Excellent	Very slight	Very slight
Silicon-carbide	SiC 80-90%	10.06	2300	Slightly acid	Excellent	15	Very low	Excellent	Excellent	Slight reaction with HF.	Attacked at temperatures.
Graphite	C 97%	6.60	3540	Neutral	Excellent	16	Low	Excellent	Excellent	Insoluble	Insoluble

[a]Good above 650°C.

[b]Chemically bonded.

[c]Dissociates above 1700°c.

The addition of a temperature controller provides process control capability not available with only a passive temperature indicator. The controller is a feedback system that adjusts fuel input to follow changes in gas temperature.[7] In extreme situations, the fuel input is entirely shut off to protect the incinerator. The controller thereby provides a degree of protection and a means of continual adjustment to match influent characteristics.

A flame-sensing device is useful for rapid shutdown of fuel supply in case of flame failure. This device reduces the potential for accumulation of explosive gases within the incinerator during the flame outage. It should observe both the burner and the pilot flame.

4.6.4 Operation and Maintenance of Incinerators

Proper operation of an incinerator system requires control of contaminant quantity and characteristics and requires regular maintenance of the burners. As with other particulate control devices, complete instrumentation and an effective preventive maintenance program are necessary.

4.6.4.1 Burners. Burners are high-maintenance items because of the high temperatures, refractory, and small orifices.[7] When the contaminated gas stream is used as the combustion air, fouling of the orifices and/or deposits in the air delivery lines can occur. Impurities within the oil can lead to similar problems. A second problem is improper sizing of the burner(s). This can lead to low gas temperatures resulting in incomplete oxidation of particulate matter. Burners with poorly adjusted air-fuel ratios can generate soot, which fouls downstream heat exchange surfaces.

Minimizing of burner problems is facilitated by providing a means of visually checking the flame for proper luminosity, length, and stability. Also, an adequate inventory of spare parts should be kept. If fouling continues, a precleaner may be economical. Finally, such incinerator instrumentation as the flame sensor and the temperature controller should be checked regularly.

4.6.4.2 Effluent Characteristics. Variability of effluent quantity and heat content should be minimized by controlling the process operation. Excess concentrations of combustible gases and vapors can lead to high temperature excursions, which damage the incinerator refractory or shell.

High gas flow rates lead to poor particle oxidation resulting from decreased residence time and decreased reaction temperature. Undesirable reaction products such as carbon monoxide, aldehydes, and organic acids also result from poor combustion.

Contaminants containing sulfur or chlorine compounds may be oxidized to highly corrosive species such as hydrochloric acid vapors and sulfuric acid vapors. These could attack either the refractory or the shell of the incinerator.[27] Precleaning or special materials of construction are required when these contaminants are present.

REFERENCES

1. U.S. Environmental Protection Agency. Control Techniques for Volatile Organic Emissions from Stationary Sources. Evaluation draft. February 1978.

2. Kobayashi, K. Combustion of a Fuel Droplet. In: Fifth Symposium on Combustion, Pittsburgh. Reinhold Publishing Co., New York, Pub. No. 1955, 1954.

3. Spaulding, D. B. Heat and Mass Transfer in the Combustion of Liquid Fuels. American Society of Mechanical Engineers. Published by the Institution of Mechanical Engineers, Story's Gale, London, England, September 11-13, 1951.

4. Hottel, H. C., G. C. Willians, and H. C. Simpson. Combustion of Droplets of Heavy Liquids Fuels. In: Fifth Symposium on Combustion, Pittsburgh. Reinhold Publishing Co., New York, Pub. No. 1955, 1954.

5. Nishiwaki, N. Kinetics of Liquid Combustion Processes. Evaporation and Ignition Lag of Fuel Droplets. In: Fifth Symposium on Combustion, Pittsburgh. Reinhold Publishing Co., New York, Pub. No. 1955, 1954.

6. Orning, A. A. Combustion of Pulverized Fuel--Mechanism and Rate of Combustion of Low Density Fractions of Certain Bituminous Coals. Trans. Am. Soc. Mech. Eng., Vol. 64, 1942.

7. Ross, R. Incinerators, An Operation and Maintenance of Air Pollu-Control Equipment. Technomic Publishing, 1977.

8. Danielson, J. A. (ed.) Air Pollution Engineering Manual. U.S. Public Health Service, National Center for Air Pollution Control, Cincinnati, Ohio. PHS Pub-999-AP-40, 1967.

9. Yagi, S., and D. Kunii. Combustion of Carbon Particles in Flames and Fluidized Beds. In: Fifth Symposium on Combustion, Pittsburgh. Reinhold Publishing Company, New York, Pub. No. 1954.

10. Browning, J. A., T. L. Tyler, and W. G. Kran Effect of Particle Size on Combustion of Uniform Suspensions. Ind. Eng. Chem., 49(1):142-147, January 1957.

11. Godsave, G. A. E. Studies of the Combustion of Drops in a Fuel Spray--The Burning of Single Drops of Fuel. In: Proceedings of the 4th Symposium on Combustion, Cambridge, Massachusetts. Williams and Wilkins Co., Baltimore, Maryland. Pub. No. 1953, September 1952.

12. Gregory, C. A., Jr., and H. F. Calcote. Combustion Studies of Droplet-Vapor Systems. In: Proceedings of the 4th Symposium on Combustion, Cambridge, Massachusetts. Williams and Wilkins Company, Baltimore, Maryland. Pub. No. 1953, September 1952.

13. Smith, D. F., and A. Gudmundsen. Mechanism of Combustion of Individual Particles of Solid Fuels. Ind. Eng. Chem., 23(3):277-285, March 1931.

14. Parker, A. S., and H. C. Hottel. Combustion Rate of Carbon. Ind. Eng. Chem., 28(11):1334-1341, November 1936.

15. Field, M. A., D. W. Gill, B. B. Morgan, and P. G. W. Hawksley. Combustion of Pulverized Coal. British Coal Utilization Research Association, Leatherhead, England, 1967.

16. Eckert, E. R. G., and R. M. Drake, Jr. Heat and Mass Transfer. 2nd ed. McGraw-Hill, New York, 1959.

17. Topper, L. Radiant Heat Transfer From Flames in a Turbojet Combustor. Ind. Eng. Chem., 46(12):2551-2558, December 1954.

18. Goodel, P. H. Industrial Ovens Designed for Air Pollution Control. J. Air Pollution Control Assoc., Vol. 10, pp. 234-238, 1960. (Presented at the 52d Annual Meeting of the Air Pollution Control Association, Los Angeles, California, July 22-26, 1959.)

19. Vandaveer, F. E., and C. G. Sedeler. Combustion of Gas. American Gas Assoc., Inc., New York, 1965.

20. Ingels, R. M. The Afterburner Route to Pollution Control. Air Eng., No. 6, pp. 39-42, June 1964.

21. Perry, R. H., C. H. Chilton, and S. D. Kirkpatrick Chemical Engineers' Handbook. 4th edition. McGraw-Hill, 1963.

22. Sly Manufacturing Company. Industrial Air Pollution Control. Cleveland, Ohio. Bulletin 204, 1967.

23. Weil, S. A. Burning Velocities of Hydrocarbon Flames. Inst. Gas Tech., Chicago, Illinois. Research Bulletin 30, 1961.

24. National Board of Fire Underwriters. Standards for Ovens and Furnaces. NBFU No. 864, August 1963.

25. Radier, H. H. Flame Arrestors. J. Inst. Petr., Vol. 25, pp. 377-381, 1939.

26. Underwriters Laboratories. Standards for Safety--Commerical--Industrial Gas Heating Equipment--UL. 795. November 1952, Revised 1960.

27. Trinks, W., and M. H. Mawhinney. Industrial Furnaces, 5th ed., Vol. I. John Wiley and Sons, 1961.

28. Burst, J. F., and J. A. Spieckerman A Guide to Selecting Modern Refractories. Chem. Eng., 74(16):85-104, July 1967.

29. Griffiths, J. C., and E. V. Weber. Influence of Port Design and Gas Composition on Flame Characteristics of Atmospheric Burners. American Gas Association Laboratories, Cleveland, Ohio. Research Bulletin 77, 1958.

SECTION 5

FUGITIVE EMISSION CONTROL

The failure of many areas to attain the National Ambient Air Quality Standards for particulate matter has prompted reexamination of the particulate problem. Conventional stationary emission sources have been controlled, but in many cases, fugitive emissions constitute a large percentage of total emissions;[1] thus attainment of the standards for particulate matter necessitates the control of these fugitive emissions.

5.1 SOURCES OF FUGITIVE EMISSIONS

Particulate that becomes airborne is either industrial process fugitive emissions or fugitive dust.

Industrial process fugitive emissions include particulates that are emitted from industry-related operations and that escape to the atmosphere through windows, doors, vents, and the like rather than through a primary exhaust system such as a stack, a flue, or a control system. Fugitive emissions may escape to the atmosphere from indoor manufacturing operations, materials handling, transfer, and storage operations, and other industrial processes. Sometimes they are emitted more directly to the atmosphere from out-of-doors industrial processes such as coke ovens, quarry rock crushing, and sandblasting. Fugitive emissions can result from poor maintenance of process equipment or from the operation of processes without concern for the environment; for example, they can result from leakage around coke oven doors that cannot be properly sealed because of warpage.

Fugitive dust is generally either natural or man-associated particulate that becomes airborne by the wind, man's activity, or both. Examples are windblown particulate from unpaved dirt roads, tilled farmlands, and exposed surface areas at construction sites and from duststorms.

Table 5-1 lists sources of industrial process fugitive emissions and the broad range of controls applicable to these emissions.

Table 5-2 lists sources of fugitive dust ("native soil that becomes airborne"). Although some sources are in the area of processes (for example, surface mines), they can be differentiated; overburden removal and haul roads at surface mines are fugitive dust sources, whereas removal of a product (e.g., coal) is a fugitive emission source.

5.2 CONTROL OF INDUSTRIAL PROCESS FUGITIVE EMISSIONS

As shown in Table 5-1, the following techniques are used to control process fugitive emissions: ventilation systems, process optimization, and wet suppression. Although some processes have been controlled by all three, others are controllable by only one or two of these techniques.

Selection of the proper control technique requires consideration of factors such as the industrial processing facility, the characteristics of the exhaust stream, and the secondary multimedia impacts. Selection must be site-specific.

Ease of control varies with the age and basic design of a facility. A fugitive emission control system for a new plant can be integrally incorporated into the overall design of the plant, whereas a retrofit application requires that the system be adapted to the configurations of the existing plant. The retrofit must be built within fixed-space limitations without interfering with operation of the process. In general, the more congested the plant layout, the harder it is to retrofit most fugitive emission control systems.

The location of the facility and the fugitive emission source within the facility can also affect the selection of the control technique. For example, controls required for a storage pile of fine material near a public road could differ from those for a storage pile well within the plant boundaries.

Product quality also affects control technique selection. For example, dry collection of fugitive emission may be needed so that it can be returned to the product stream. Also, wet suppression may have limited use because it has an adverse impact on product quality.

TABLE 5-1. INDUSTRIAL PROCESS FUGITIVE EMISSION SOURCES AND APPLICABLE CONTROL TECHNIQUES[2]

Source	Ventilation and collection	Process optimization	Wet suppression
Material handling			
Transferring/conveying	x	x	x
Loading/unloading	x	x	x
Storage	x	x	x
Bagging/packaging	x		x
Material crushing and screening	x	x	x
Mineral mining			
Drilling	x		
Blasting		x	
Extraction		x	x
Waste disposal (tailings)			x
Metallurgical operations			
Furnace charging	x	x	
Furnace tapping (product and slag	x	x	
Casting	x	x	
Mold preparation	x	x	x
Casting shakeout	x	x	
Slag disposal		x	x
Sintering	x	x	
Coke oven charging		x	
Coking (leaks)		x	
Coke pushing	x	x	
Coke quenching		x	

TABLE 5-2. FUGITIVE DUST EMISSION SOURCES AND APPLICABLE CONTROL TECHNIQUES[2,3]

Source	Wet suppression	Stabilization	Speed reduction	Surface cleaning/transportation controls	Windbreaks	Good operating practices
Unpaved roads	x	x	x			
Construction activities	x			x		x
Dust from paved roads				x		
Off-road motor vehicles			x			
Overburden removal/storage	x					x
Reclamation efforts		x				x
Inactive tailings piles		x			x	
Disturbed soil surfaces		x			x	x
Agricultural tilling					x	

The major exhaust stream characteristics that collectively influence selection of the control technique include particle size distribution; temperature, moisture content, presence of corrosive gases; and physical and chemical characteristics and associated toxicity of the particulate.

The size of particulates from many metallurgical fugitive emission sources is predominantly below 5 μmA, which in the case of add-on control systems often dictates the need for a fabric filter.[4] Exceptions are sources in which the particulates have a relatively large diameter, which sometimes can be sufficiently controlled by high efficiency cyclones.

Since most process fugitive emission exhaust streams are at either in-plant or ambient temperatures, provisions such as heat-resistant fabric filter material for excess temperatures are generally not required. In some applications, however, hoods near furnaces must be water-cooled to withstand initial high temperatures. Because most fugitive emissions have approximately the same moisture content as the ambient or in-plant air, little insulation or reheat is generally needed for protection against condensation.

Physical and chemical characteristics of fugitive emissions also influence selection of the control technique. The most critical physical characteristics that relate to the type of control and to the material of construction are abrasiveness (related to particle size and morphology), hygroscopy, and true density; the most critical chemical characteristic is corrosiveness.

Control of fugitive emissions can create secondary multimedia environmental effects, which also must be controlled. These secondary effects include solid waste disposal, water pollution, generation of additional fugitive emissions, and noise. If not controlled, problems associated with poor procedures for disposal of the fugitive emissions collected in a fabric filter (when return to the processing system is not feasible) may exceed the original problem. An example would be dumping collected materials into an open truck, hauling them in an open truck to a landfill, and dumping them into a landfill that is not adequately protected from wind erosion and surface runoff. Thus adequate precautions must be taken in the selection of a control technique, to avoid creating new fugitive sources.

5.2.1 Ventilation Systems

5.2.1.1 Localized Hooding and Enclosure. Capture and ventilation systems are used with appropriate particulate removal devices (e.g., a fabric filter or wet scrubber) to control fugitive emissions. Sources amenable to this type of control include processes such as materials handling (conveyors, elevators, feeders, loading and unloading, product bagging, and storage silos); solids beneficiation (crushing, screening, and other classifying operations); mining (drilling and crushing), and others (furnaces, dryers).[2,4-8]

In general, systems of capture near the process (localized hoods or canopy hoods), as opposed to ventilation of an entire building, are desirable from an economic and occupational exposure standpoint. For example, the use of canopy hoods to control fugitive emissions from electric arc furnaces can be expected to require 40 to 50 percent of the flow rate required for building evacuation.[4] Local hoods (nearer the emission source than canopy hoods) may require even less air flow for capture.

The capture effectiveness of a ventilation system varies greatly and depends on many parameters. The properties of the emission source, location of the hood or enclosure, possibilities of external disturbances such as wind and vibrations, and operator errors can all affect the capture efficiency. In general, however, capture efficiencies of more than 90 percent can be expected with proper design. For example, 90 percent efficiency is attainable on the enclosure of basic oxygen furnaces.[8]

Detailed guidelines for the proper design of ventilation systems can be obtained from several sources.[9-11] The important factors in the proper design of hooding, enclosures, ducting, and ventilation are:

- Hood design and placement
- Air velocity and flow direction required for proper capture of particles
- Volume of air required
- Minimization of static pressure drop.

Hoods should be designed to enclose the emission source as much as possible. Total enclosure, however, may be limited by the need for easy access to the process. Hoods must have adequate flow rates and face velocities (air into the hood) to capture the particles and to impose minimum pressure drop on the system. Sometimes the hood can be located and shaped so that it is aligned with the general flow direction of the contaminant.

Air flow past the emission source must be sufficient to capture the contaminant, and must be directed to minimize exposure of workers to hazardous fumes. Proper air flow rates depend on the specific properties of the emission stream and the particulate matter. Duct systems must complement the hoods in efficiency of operation. Fittings and other components should be adequate to prevent excess pressure drop. When overall hood and duct dimensions are selected, the expected static pressure drop in the system can be calculated readily by using standard techniques.[11]

5.2.1.2 Building Evacuation. General ventilation of an entire building is receiving increased attention as a technique of fugitive emission control because of the space entailed in capturing emissions with many local hoods.[2] Ductwork is installed on the building roof, and large fans draw the particulate-laden gases from the building through a collection device. This may require improvement of roof supports because of the added weight, and the installation of opening/closing doors to minimize leaks. A fabric filter is typically the control device selected for building evacuation. Overall capture and collection efficiency for such a device is estimated to be from 90 to more than 95 percent.[5]

Total building evacuation has its drawbacks, however. One is the large air flow rates required. Another is that the evacuation systems sometimes collect enough gas to sufficiently ventilate the workplace overall, but still leave an unacceptable level of local pollutant concentrations because of "deadspots" in the air flow pattern.[5]

Building evacuation systems have been applied to electric arc furnace melt shops in the iron and steel industry and to a converter building in the copper industry.[5] These systems range in size from 235 to 285 m^3/s and larger.[5]

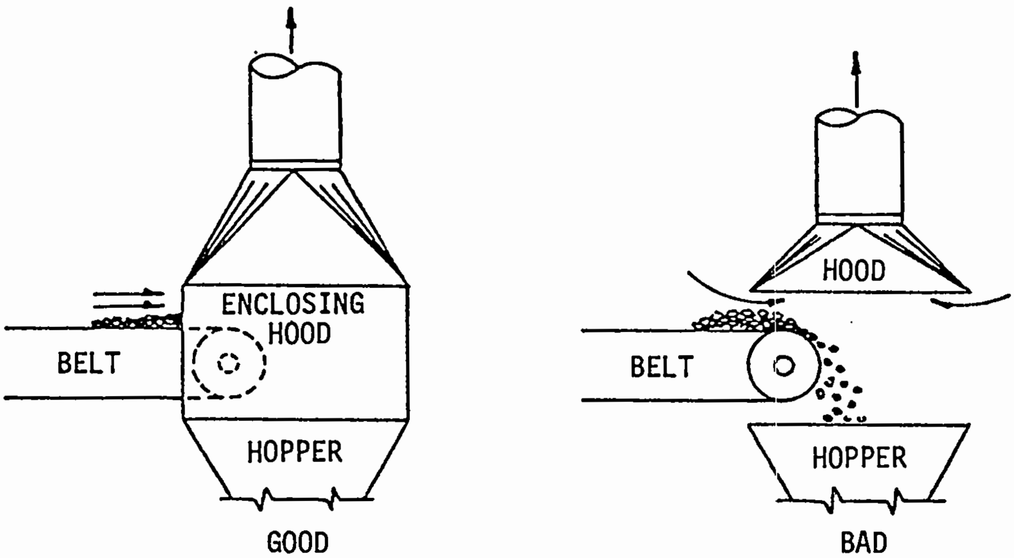


Figure 5-1. Hood design.[9]

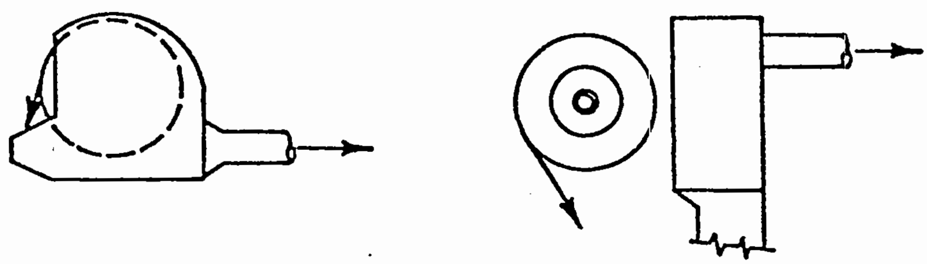


Figure 5-2. Hood location.[9]

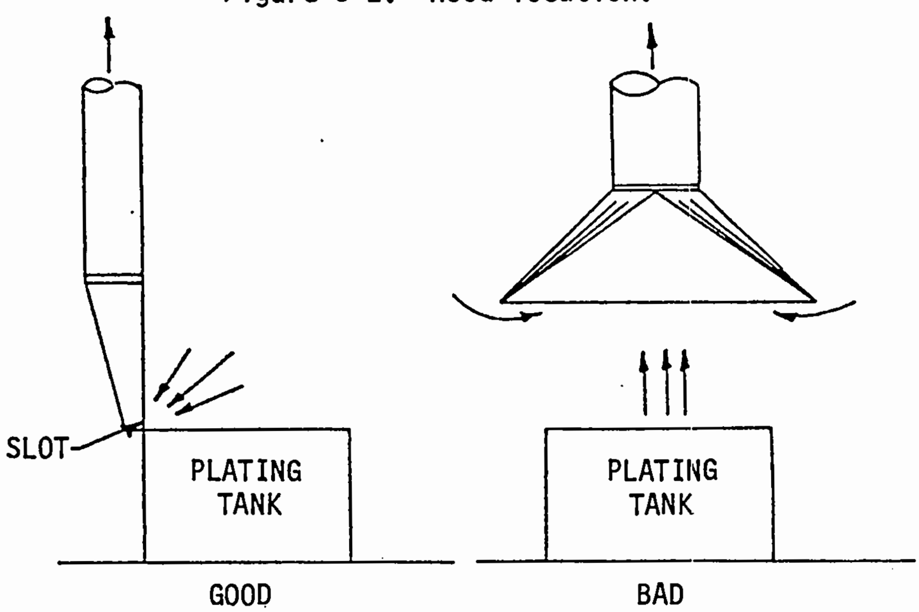
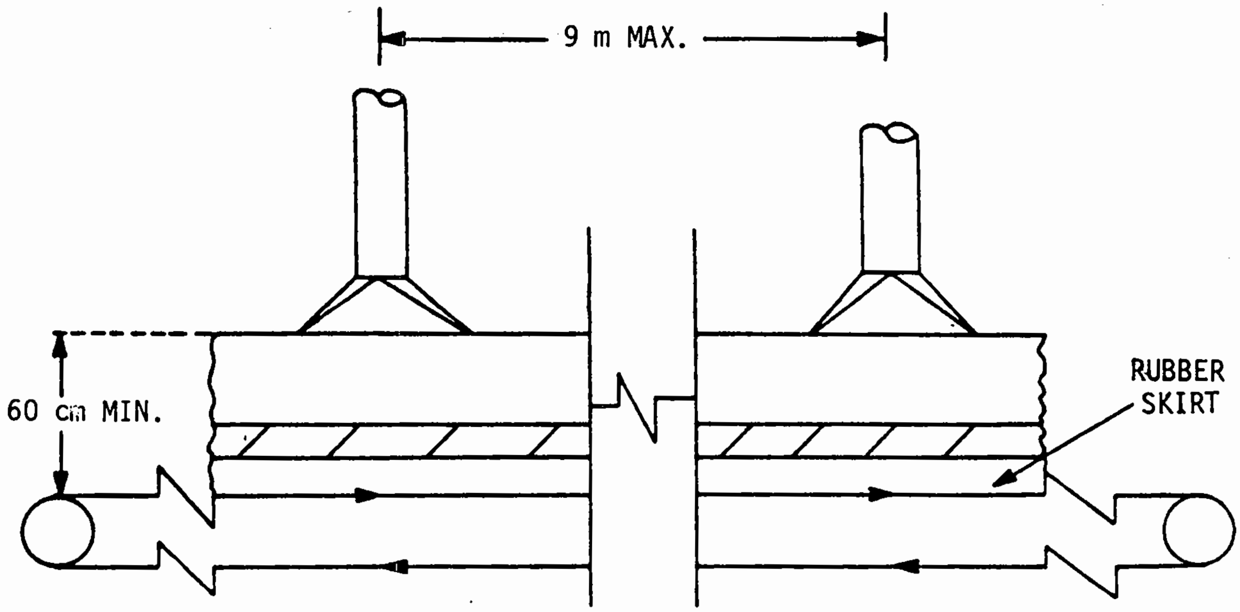


Figure 5-3. Air flow direction.



COVER CONVEYOR BETWEEN TRANSFER POINTS.
EXHAUST AT TRANSFER POINTS AS REQUIRED.
EXHAUST MINIMUM ADDITIONAL 0.5 m^3/s per in. OF BELT WIDTH AT A MAXIMUM OF 9-m INTERVALS.
ENTRY LOSS = ENTRY LOSS FACTOR FOR TAPERED HOOD X DUCT VELOCITY PRESSURE.
DUCT VELOCITY = 1100 m/min MINIMUM.

Figure 5-4. Belt conveyor ventilation for fugitive emissions control.[10]

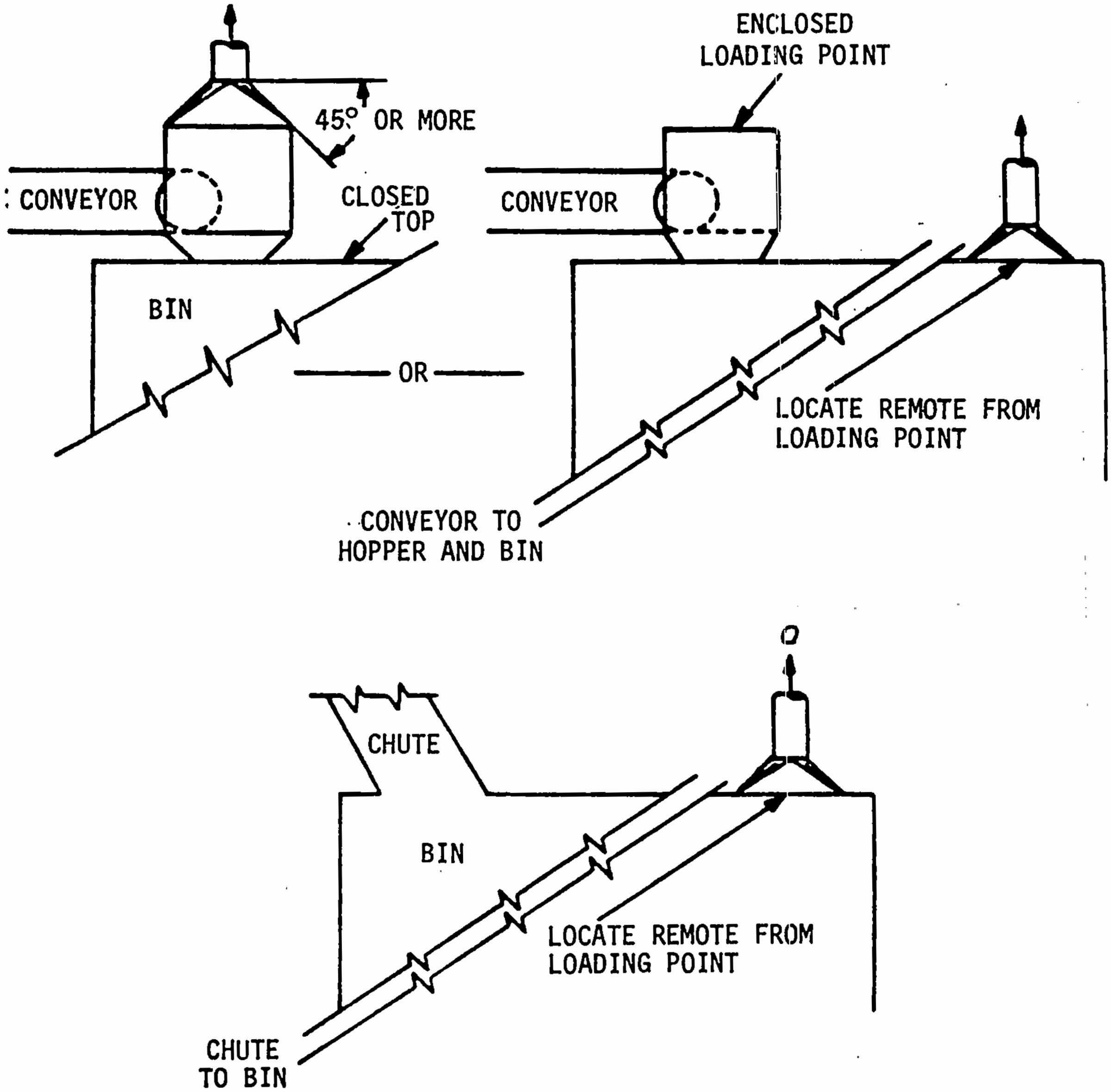


Figure 5-5. Hopper and bin chute and conveyor-loading ventilation for fugitive emissions control.[10]

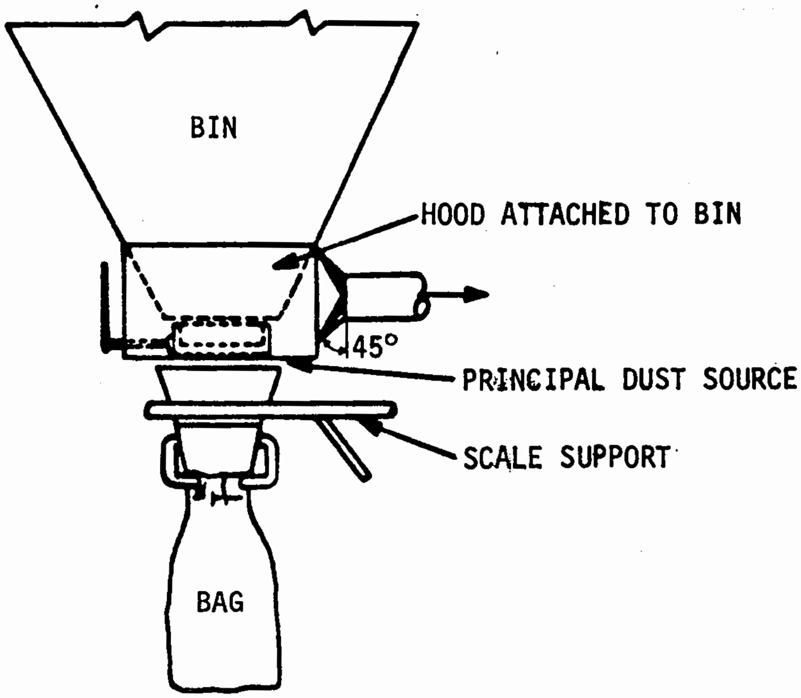


Figure 5-6. Bag-filling fugitive emissions control.[10]

5.2.2 Optimization of Equipment and Operation

Control by proper operation and maintenance practices primarily involves the elimination of fugitive emissions resulting from process upsets, leaks, and poor housekeeping. In addition, prompt cleanup of spills on the ground or floor by vacuum systems will prevent spills from becoming airborne. A full-time cleanup crew may be required in some industries. Also included in this category is the optimization of the capture efficiency of the hooding systems of primary source control devices. Examples include:

Precautions to ensure that a cupola is not overloaded, to eliminate the possibility of backpressure from the primary control system and "puffing" fugitive emissions from the charging door opening

Maintenance of coke oven doors and seals to eliminate leaks during coking

Prompt repair of electric arc furnace hooding damaged by overhead charging crane

Conscientious periodic application of chemical suppressant to inactive storage piles and tailings areas

Increase in the vent rate of a canopy hood system for an electric arc furnace in a gray iron foundry

Prompt cleanup of spills from trippers of a clinker conveying system in a portland cement plant

Increase in the vent rate of a primary control device to eliminate or minimize leaks.

A change in the process or raw materials can be an effective technique of reducing fugitive emissions. For example, using only clean scrap in metal-melting furnaces or removing crankcase oil prior to automobile salvage can reduce fugitive emissions. Changing the process (from cupola to electric arc furnace or from bucket elevator to pneumatic conveyor) is an effective way to minimize fugitive emissions at the source.

During the transfer of dusty materials from a conveyor or stacker to another conveyor or stockpile, fine materials can be separated from large materials by wind and/or the falling action of the materials. A simple technique for reducing dusting is to shorten the fall distance by using hinged-boom conveyors, rock ladders, telescoping chutes, lowering wells, or other devices.[12] The hinged-boom conveyor, which can raise or lower the conveyor belt and thus reduce the fall distance at the transfer point, can reduce emissions by an estimated 25 percent.[4] Rock ladders allow the material to fall short distances in a steplike fashion; the direction of travel on successive steps is reversed to reduce the momentum that the material receives from the previous fall and to reduce the resulting dusting. This technique can reduce emissions by 50 percent.[4] Telescoping chutes carry the materials from the discharge point to the receiving point, but the materials are not exposed. Estimated control efficiencies of 75 percent are possible. Lowering wells, or perforated pipes, allow materials to flow out of the pipe above the pile surface; The dusting from the impact of the falling materials is retained inside the pipe, and the material is protected from wind action. This technique can reduce emissions by an estimated 80 percent.[4]

Confinement by covering or enclosure basically involves the partial or complete seclusion and/or shielding of the source of the fugitive dust or the industrial process fugitive emissions. The design strategy is to prevent the fugitive particulate matter from becoming airborne by the wind or by the mechanics of the process. These control techniques range from small enclosures over conveyor transfer points (for protection from the wind and from turbulence of the moving belt) to building structures (for complete confinement of materials storage areas). Other examples include conveyor system enclosures, weighted tarpaulin covers for inactive material storage piles, partial windbreaks in the prevailing upwind direction from limestone quarry surge pile areas, and partial open-ended shelters with shrouds for railroad car loading and unloading.[2] The total enclosure of a transfer point can reduce fugitive emissions by an estimated 70 percent.[4]

5.2.3 Wet Suppression[2,4,5]

Fugitive emissions from materials handling and beneficiation can be controlled by spraying liquid on the materials. Wet suppression techniques include applications of water, chemicals, and foam. The point of application is most commonly at the conveyor feed and discharge points, but some are at conveyor transfer points and equipment intakes. Wet suppression with water only is a relatively inexpensive technique; however, it has the inherent disadvantage of being short-lived. Control with chemicals (added to water for improved wetting) or foam is longer lasting, but more expensive than water alone. A wet suppression system is shown in Figure 5-1.

A wetting agent breaks down the surface tension of water, and allows it to spread further, penetrate deeper, and to wet the small particles better than untreated water. Mechanical agitation of the materials causes the small particles to agglomerate. For effective control, the spray should be applied at each point where the particles might be fractured, allowed to free fall, or subjected to strong air currents.[14]

When applied to loading or unloading operations, wet suppression techniques can reduce airborne dust to some extent. The loading process naturally disturbs the materials, but water sprays with wetting agents cause small dust particles to adhere to larger pieces so as not to become entrained. This technique is not suitable for many materials that cannot be readily wetted.[2]

Foam is effective in dust suppression because small particles (1 to 50 μmA in diameter) break the surface of the bubbles in the foam when they come in contact with it, and these particles become wetted. (Larger particles only move the bubbles away.) The small wetted particles then must be brought together or brought in contact with larger particles to achieve agglomeration. If foam is injected into free-falling aggregate at a transfer point, the mechanical motion causes the contact of particle with bubble and subsequent contact of particle with particle.

Electrostatically charged fog is another type of wet suppression system. It differs from conventional water sprays, in that the droplets carry a charge of static electricity. Because most fine particulates carry a natural electrical charge, particle collection can be improved via electrostatic attraction if the water spray droplets are charged to the opposite polarity. The charged water droplets exert attractive forces on the oppositely charged particles, and each droplet collects more particles as it travels through the dust-laden gas.[5,15]

Spray systems on material-handling operations are estimated to reduce emissions by 70 to 95 percent.[4] Spray systems achieve an estimated 80 percent reduction at railcar unloading stations at iron and steel plants.[4]

Spray systems can also reduce load-in and wind erosion emissions from storage piles of various materials. Emissions from load-in can be reduced

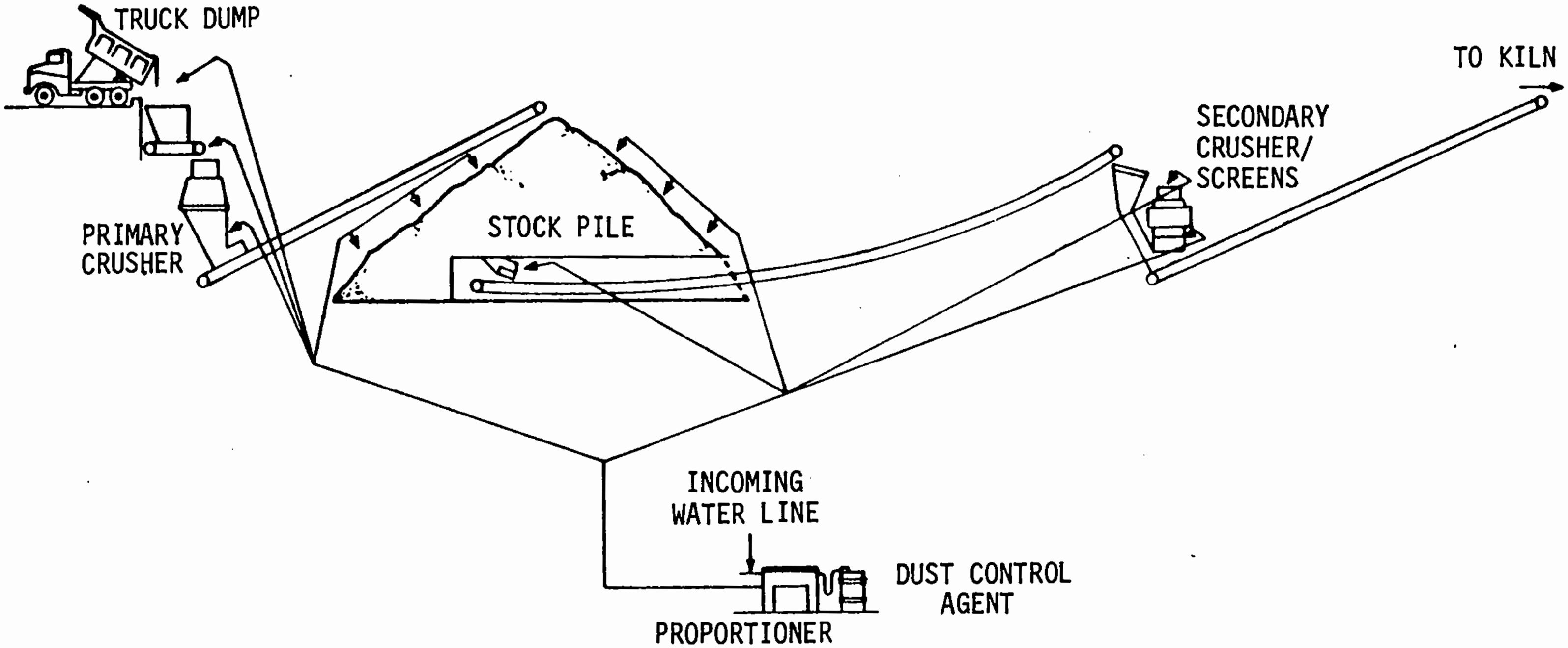


Figure 5-7. Wet dust suppression system applied to material handling operation.[13]

Note: Wet suppression at fine mesh screens must be regulated properly to avoid blinding of screens.

by an estimated 70 to 90 percent,[2,4,16] and wind erosion can be reduced by an estimated 80 to 90 percent.[2,4]

5.3 CONTROL OF FUGITIVE DUST

Table 5-2 lists the major fugitive dust sources and the applicable control techniques. These techniques are wet suppression; stabilization (physical, chemical, and vegetative); and specialized methods such as speed reduction, street cleaning, windbreaks, industrial transportation control, and good operating practices.

5.3.1 Wet Suppression[2,4]

Wet suppression of dust with water or with water plus a wetting agent (surfactant) is an effective temporary control for fugitive dust from unpaved roads, cattle feedlots, stockpiles, waste heaps, mining, and construction activities. Water alone is not as effective because the high surface tension of water prevents it from wetting, spreading, and penetrating. The addition of a wetting agent aids water penetration into the material and helps to promote particle agglomeration.[17] Wet suppression of fugitive dust on exposed surfaces such as haul roads is usually accomplished by spraying from tank trucks. Fixed pipeline spray systems have also been used on main haul roads that are relatively permanent, such as those at mines and large industrial facilities.

When water is used for wet suppression, repeated applications are necessary. Evaporation and runoff cause its effectiveness to be temporary. In some regions, water usage is limited as a suppressing agent because of its scarcity.

The control efficiency of wet suppression techniques depends on local climatic conditions, the properties of the fugitive source, and the length of effectiveness provided by the control. Estimated control efficiencies of 80 percent have been reported for cattle feedlots.[16] Extensive watering of the soil may reduce emissions from construction operations as much as 70 percent.[16] Wetting of access roads twice a day with 2.3 liters of water per square meter will suppress fugitive dust from normal construction practices an estimated 30 to 50 percent.

5.3.2 Stabilization

Stabilization techniques isolate fugitive dust sources from external disturbances such as wind and traffic. This can be done physically by adding a layer of material on exposed surfaces; chemically by using materials that help to bind dust and particulates; and vegetatively by planting of trees, shrubs, and grass over the surface.

5.3.2.1 Physical Stabilization. For inactive waste stockpiles and steep slopes, stabilization can be accomplished by mixing a layer of rock, soil, crushed or granulated slag, bark, wood chips, and straw with the top layer.[18] For dirt roads, paving is the most effective control. The most widely used low-cost pavement is a bituminous asphaltic chip seal over a granular base or a stabilized soil base. Maintenance requirements depend on vehicle traffic and locale, but they generally include a second chip seal after 1 year, followed by another in approximately 5 years. Gravel is sometimes used on unpaved roads, but it is less effective than the chip seal.[19] In one study of road paving, an estimated 85 percent control efficiency was cited.[16] In a study comparing various methods of controlling emissions from unpaved roads in Arizona, gravel paving of unimproved dirt roads produced an estimated annual control efficiency of 50 percent.[3]

Road carpets are a recent development for controlling fugitive dust from unpaved roads. A water-permeable polyester fabric is laid between the roadbed (subsoil) and the coarse aggregate (e.g., gravel or crushed rock) road ballast, which separates the fine soil particles in the roadbed from the coarse aggregate. This fabric prevents fine materials from reaching the road surface and thereby reduces fugitive dust. Any fine materials (<15 μmA) in the road surface would be washed into the road ballast during rainfall. Fine dust in the ballast passes through the fabric into the subsoil or to the edge of the road, but fines in the subsoil cannot be pumped up into the ballast. It is the minimization of fines in the road surface material that effects the reduction in fugitive dust.[20]

5.3.2.2 Chemical Stabilization. Chemical stabilization requires the use of materials that, upon drying, bind with surface particles to form a protective crust. It acts in much the same way as physical controls (by isolating the surface from climatic factors), and it is often used in combination with vegetative stabilization. Chemical stabilization can be applied to unpaved roads and airstrips, to waste or tailings piles, to disturbed soil surfaces, or to reclaimed areas. Many types of chemical stabilizers are available, and they can be applied with water or separately.

Approximately 400 hectares of the inactive Kennecott Copper tailings area west of Salt Lake City have been successfully stabilized by aerial chemical applications.[21] Estimated control efficiencies of chemical stabilization for a variety of sources are as follows.[14]

Source	Efficiency, %
Unpaved roads	50
Construction--completed cuts and fills	80
Tailings piles	80
Cattle feedlots	40

The effectiveness of chemical stabilization on unpaved roads varies according to the amount of traffic. Because heavy traffic tends to break up the surface crust and to pulverize particles, it causes greater entrainment of particles into the atmosphere.

The results of a study of various chemical stabilizers for dust control on unpaved roads were encouraging.[19] The stabilizers were applied to sections of an unpaved road with an average daily traffic of 140 vehicles and with a surface soil silt content of 28 percent. Some of the chemicals were applied to the surface by spray and others were mixed to a depth of 7.6 cm and then compacted. After 5 months of surface stabilization, control efficiencies of 83 to 95 percent were still being achieved. After 14 months and several bladings, control efficiencies ranged from 9 to 54 percent, depending on the chemical used. When road stabilizers were worked into the road surface, reductions in emissions of 80 to 95 percent were achieved after 5 months, and 12 to 84 percent after 14 months and several bladings. These results show that working the stabilizer into the road surface causes it to remain effective longer.[3,19]

5.3.2.3 Vegetative Stabilization. Vegetation is effective in the stabilization of a variety of exposed surfaces. In many cases, modifications first must be made to the surface or the surrounding terrain.

Sometimes, physical and chemical stabilization techniques are used with vegetative stabilization. Vegetative stabilization is restricted to inactive areas where the vegetation will not be mechanically disturbed once it has been planted. Emission sources that can be controlled by vegetative covers include mineral waste piles, road shoulders, reclaimed land, and disturbed soil surfaces.[3,16]

In coal mining and preparation, both fine and coarse waste materials (low-grade coal, ash, carbonaceous and pyrite shale, slate, clay, and sandstone) are produced. Because coal wastes are acidic, they must be treated chemically and physically before vegetative stabilization can be implemented effectively. Chemical treatment involves the addition of an alkaline material such as limestone, fly ash, phosphate rock, or treated municipal sewage sludge. Physical treatment involves covering the waste with soil so that it will support vegetative growth. The use of acid-tolerant vegetative species is recommended even when the soil has been neutralized.

Mineral mining and beneficiation produce wastes in the form of overburden, gangue, and tailings. Vegetative stabilization is normally no problem with overburden and gangue, but it may be difficult to apply to tailings because of a lack of nutrients, a concentration of saline or toxic compounds, and extreme pH conditions. Tailings piles therefore must be treated or covered with topsoil.

Control efficiency of vegetative stabilization varies considerably according to the amount and type of cover. One report estimated a control efficiency of 50 to 80 percent on tailings piles.[16] In areas that are less than hospitable to plant growth (e.g., the arid Southwest), reductions in fugitive dust could be as little as 25 percent;[3] whereas reductions could approach 100 percent in areas that easily support dense vegetative covering.

5.3.3 Specialized Fugitive Emission Control Techniques

Some fugitive dust control techniques are relatively specific to certain processes, and thus are not as widely applicable as those just discussed. Sometimes they are used to augment some of the techniques already described.

5.3.3.1 Speed Reduction. Reducing the speed of vehicles traveling over unpaved roads can lower the fugitive dust emissions because it reduces turbulence. Speeds of less than 48 km/h cause emissions to vary in proportion to the square of the vehicle speed.[22] Based on uncontrolled speeds of 64 km/h, reduced speeds would produce the following estimated reductions in fugitive dust from unpaved roads.[23]

Vehicle speed, km/h	Estimated emission reduction, %
64	0
48	25
32	65
24	80

5.3.3.2 Street Cleaning. Street cleaning has been proposed as a technique of reducing reentrainment of dust from paved roads. Essentially, three types of cleaners are now in use: broom sweepers, vacuum and regenerative-air sweepers, and flushers. Broom sweepers use a rotating gutter broom to sweep material from the gutter into the main pickup broom, which rotates to carry the material into the truck hoppers. The regenerative air-sweeper uses an air blast to direct material into a collection hopper, and flushers use jets of water to move material to the gutters.[3]

Results of field studies examining municipal street-cleaning techniques in Kansas City, Cincinnati, and other cities were inconclusive; most of the data showed that cleaning produced no effective reduction in emissions.[3,24] Estimates of the effectiveness of cleaning paved roadways at industrial facilities have estimated efficiencies of broom sweeping, vacuum sweeping, and water flushing have been estimated at 70, 75, and 80 percent, respectively.[4] The broom and vacuum sweeping control efficiencies were based on biweekly cleaning, and the water flushing was based on weekly cleaning.

5.3.3.3 Industrial Transportation Control. Another techniques for controlling fugitive dust from paved or unpaved roads at industrial facilities is to reduce the amount of vehicular traffic by providing perimeter parking and by bussing employees to their work areas. This technique has been used at western coal mines and at an iron and steel plant.

The reduction in emissions that can be achieved by transportation control is directly proportional to the reduction in vehicular traffic. This type of control can be used with paving and street cleaning.

5.3.3.4 Windbreaks. Wind contributes significantly to fugitive dust emissions. Reduction of surface windspeed by erecting physical barriers (windbreaks) perpendicular to the wind direction is a logical technique for reducing emissions. Windbreaks surrounding an agricultural field can reduce soil erosion. The effectiveness of a windbreak extends downwind for a distance of 10 times the barrier height.[25] A barrier 7.6 m in height will control erosion 76 m downwind of the barrier. Windbreakers can reduce erosion by 12 percent on a typical 600-m long field; they are, however, generally considered infeasible for the control of large fields.[3]

5.3.3.5 Good Operating Practices. Good operating practices can minimize fugitive dust from construction and from earthmoving activities. Such practices include the following.[2,3]

Minimizing fall distances when dumping material from frontend loaders

Washing vehicle undercarriages prior to their leaving construction sites (to eliminate mud carryout)

Limiting, by proper scheduling of activities, the exposure time of cleared land

Little information is available on the reduction of fugitive dust that could be achieved by good operating practices; however, reductions in emissions should be proportional to reductions in dust-generating activities.

REFERENCES

1. Dunbar, D. R. Overview of the Fugitive Emission Problem--1979 SIP Revisions. Presented at the 3rd Symposium on Fugitive Emissions: Measurement and Control, San Francisco, California, October 23-25, 1978. EPA-600/7-79-182, August 1979.

2. Jutze, G. A., et al. Technical Guidance for Control of Industrial Process Fugitive Particulate Emissions. EPA-450/3-77-010, March 1977.

3. Richard, G., and D. Safriet. Guideline for Development of Control Strategies in Areas with Fugitive Dust Problems. EPA-450/2-77-029, October 1977.

4. Bohn, R., T. Cuscino, Jr., and C. Cowherd, Jr. Fugitive Emissions From Integrated Iron and Steel Plants. EPA-600/2-78-050, March 1978.

5. Daugherty, D. P., and D. W. Coy. Assessment of the Use of Fugitive Emission Control Devices. EPA-600/7-79-045, February 1979.

6. Wallace, D., and C. Cowherd, Jr. Fugitive Emissions from Iron Foundries. EPA-600/7-79-195, August 1979.

7. Standards Support and Environmental Impact Statement Volume I: Proposed Standards of Performance for Grain Elevator Industry. EPA-450/2-77-001a, January 1977.

8. Nicola, A. G. Fugitive Emission Control in the Steel Industry. Iron and Steel Engineer 53(7):25, July 1976.

9. American Conference of Governmental Industrial Hygienists. Industrial Ventilation, A Manual of Recommended Practice. 14th ed. Committee on Industrial Ventilation, Lansing, Michigan, 1976.

10. Hagopian, J. H., and E. K. Bastress. Recommended Industrial Ventilation Guidelines. Department of Health, Education and Welfare, Pub. No. (NIOSH) 76-162, January 1976.

11. American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc. ASHRAE Handbook and Product Directory, 1976 Systems. New York. 1976.

12. Weant, G. E., III. Characterization of Particulate Emissions for the Stone-Processing Industry. Research Triangle Institute, Research Triangle Park, North Carolina. May 1975.

13. PEDCo Environmental, Inc. Reasonably Available Control Measures for Fugitive Dust Sources. Prepared for Ohio Environmental Protection Agency. March 1980.

14. Jutze, G. A., and K. Axetell. Investigation of Fugitive Dust. Vol. I. Sources, Emissions and Control. EPA-450/3-74-036a, June 1974.

15. Hoenig, S. A. Fugitive and Fine Particle Control Using Electrostatically Charged Fog. EPA-600/7-79-078, March 1979.

16. Siebel, R. J. Dust Control at a Transfer Point Using Foam and Water Sprays. U.S. Department of the Interior, Bureau of Mines. Pub. No. TPR 97, 1976.

17. Evans, R. J. Methods and Costs of Dust Control in Stone Crushing Operations. U.S. Department of the Interior, Bureau of Mines. Pub. No. 8669, 1975.

18. Dean, K. C., R. Havens, and M. W. Glants. Methods and Costs for Stabilizing Fine-Sized Mineral Wastes. U.S. Department of the Interior, Bureau of Mines. RI 7896, 1974.

19. Sultan, H. A. Soil Erosion and Dust Control of Arizona Highways. Part IV. Final Report Field Testing Program. Arizona Department of Transportation, November 1976.

20. Blackwood, T. R. Assessment of Road Carpet for Control of Fugitive Emissions from Unpaved Roads. EPA-600/7-79-115, May 1979.

21. Jutze, G. A., K. Axetell, and R. S. Amick. Evaluation of Fugitive Dust Emissions from Mining. EPA-600/9-76-001, 1976.

22. Cowherd, C., Jr., K. Axetell, C. M. Guenther, and G. A. Jutze. Development of Emission Factors for Fugitive Dust Sources. EPA-450/3-74-037, June 1974.

23. Compilation of Air Pollutant Emission Factors. AP-42, July 1979.

24. Axetell, K. Control of Reentrained Dust from Paved Streets. EPA-907/9-77-007, July 1977.

25. How to Control Soil Blowing. U.S. Department of Agriculture. Farmers Bulletin, No. 2169, July 1961.

SECTION 6

ENERGY AND ENVIRONMENTAL CONSIDERATIONS

Energy is consumed in the operation of particulate control systems. Determining the optimum energy usage rate for an installation involves careful balancing of performance requirements, availability requirements, and operating costs. Energy demands of conventional particulate control systems, discussed in Section 6.1, emphasize the potentials for and the limitations of energy conservation. Some control devices have the potential for generating small quantities of secondary pollutants, not originally present; environmental impacts of these pollutants are discussed in Section 6.2.

Particulate control devices concentrate the particulate matter entrained in a gas stream into a solid or liquid effluent stream for disposal by alternative means. If disposal of the concentrated particulate is handled improperly, the original air pollution problem can become a water pollution or a solid waste problem. Environmental factors considered in disposal of wastes collected in particulate control devices are addressed in Sections 6.3 and 6.4. Other environmental considerations associated with the operation of particulate control devices include noise management and radiation control; these considerations are discussed in Sections 6.5 and 6.6.

6.1 ENERGY REQUIREMENTS

The goal of any evaluation of energy usage is to identify means of minimizing the energy demand without sacrificing system performance or predisposing the system to future maintenance problems. A complete and realistic energy inventory is the basis for such an optimization program.

The energy requirements of a control system are simply the sum of the energy requirements of each component. Accordingly, in the following sections, the energy demands for major components are evaluated as a function of gas flow rate; the total system energy requirements are the sum of the energy demands of each component at that flow rate. The results are estimates which indicate the relative importance of various energy demands within the systems. Optimization of energy usage is based on these estimates.

6.1.1 Fan Energy Requirements

Each control device introduces a static pressure loss into the effluent gas-handling system. Typical values are shown in Table 6-1. The hoods and ducts, both before and after the control device, introduce additional static pressure losses (1 to 10 kPa). The fan must be sized to deliver the desired gas flow rate at the total static pressure drop associated with the control system.

TABLE 6-1. TYPICAL STATIC PRESSURE

Control device type	Range of static pressure loss, kPa[a]
Electrostatic precipitator	0.1- 0.5
Mechanical collector	0.2- 1.0
Fabric filter	0.5- 2.5
Wet scrubber	0.5-25.0

[a]To convert kPa to inches of water, multiply by 4.019.

To calculate the portion of total fan energy that is chargeable to the control device (as opposed to the ventilation system for the process), the fan curves must be analyzed. A comparison is made between power requirements at the actual operating point and power requirements for a similar fan system without the control device static pressure loss. Subtraction yields the incremental energy requirements due to the particulate control device. Approximate incremental fan energy requirements due to the total pressure losses of the ventilation system and the control device are shown in Figure 6-1;[1,2] these general curves do not apply to any specific facility or manufacturer. These incremental energy requirements must be adjusted for the gas temperature change during passage through the system. Most control

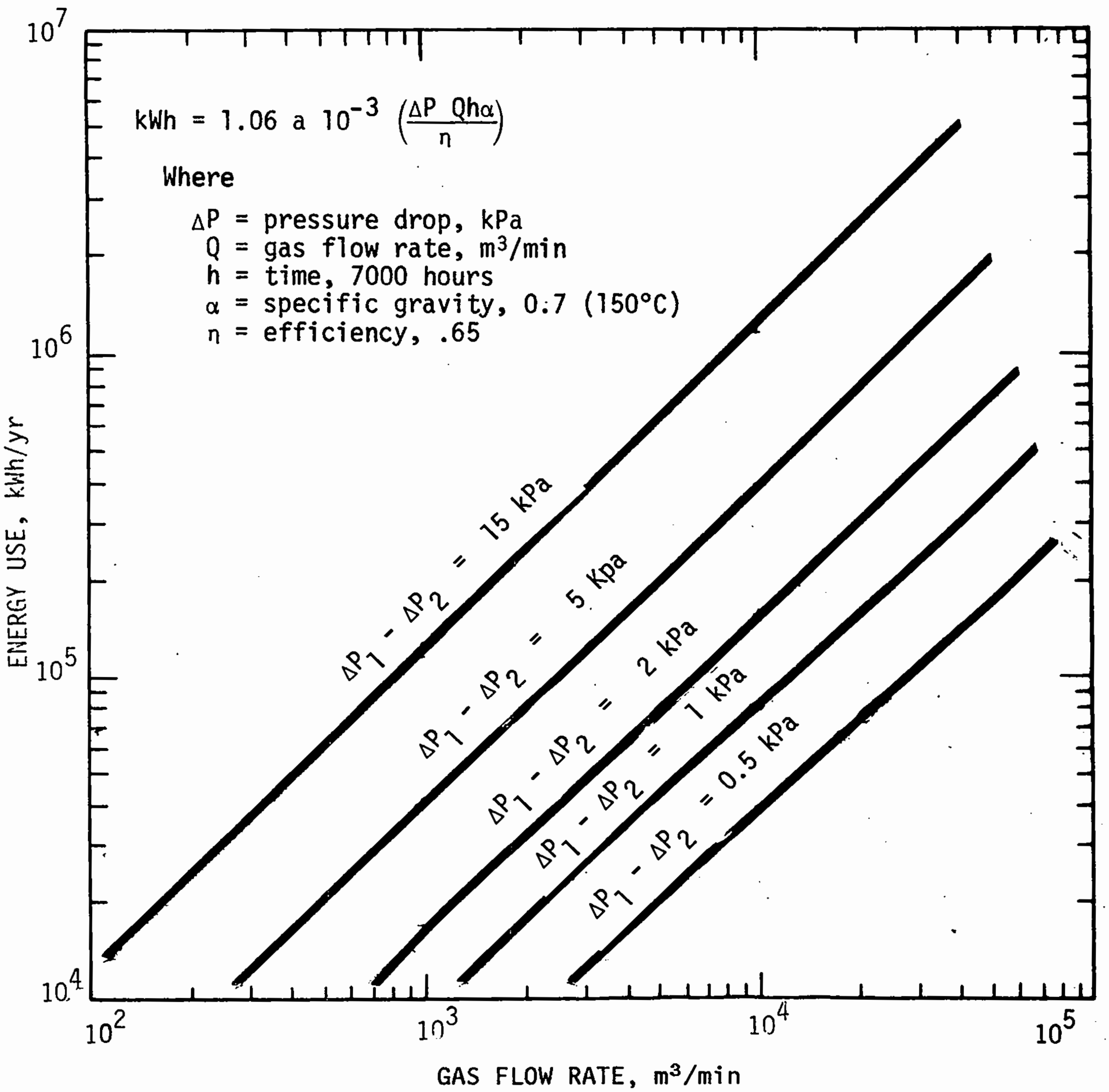


Figure 6-1. Incremental energy requirements for fans.

devices cool the gas stream 5° to 25°C. At lower temperatures, power requirements are greater because the density of the gas is increased.[4]

One means of reducing incremental fan energy requirements is to minimize static pressure losses. With electrostatic precipitators, this may be accomplished by a smoother gas entry and exit the box. Better gas distribution yields energy savings at the same time that performance is improved. With fabric filters energy reduction may result from more frequent cleaning, which allows a lower average static pressure drop across the fabric and dust cake. For all other types of particulate control devices, a decrease in static pressure drop is normally associated with a reduction in performance.

The ventilation system gas flow may be improved. All sharp squared-off turns in ducting should be replaced by smooth gradual turns having lower flow resistance.[1] Likewise, transitions in duct size should be as gradual as possible. Unnecessary turns should be eliminated. Flow of the gas stream into and out of the fan is particularly important.[1,2,3]

Reductions in gas flow requirements due to movement of the hood closer to the particulate generation source could have a substantial impact in that static pressure loss through ductwork is proportional to the square of the gas flow rate.[1] Insulation and sealing of ducts (to reduce cold air inleakage) may be effective on large systems transporting gas at elevated temperatures.

For cyclic processes, the fan may be shut down or dampered down when ventilation is not needed. There is a risk, however, that the gas temperatures will repeatedly pass below the acid and water dewpoints, and lead to corrosion. Care must be exercised when a particulate control system is temporarily shut down.

6.1.2 Control Device Energy Requirements

Generalized energy demand requirements are presented for conventional particulate control devices. These do not include requirements for hopper heaters and vibrators or for solids transport equipment, both of which are discussed separately. These estimates represent approximate values only.

6.1.2.1 Fabric Filter Subsystems. The fabric cleaning apparatus is the dominant energy consumer within the control device. The total energy requirements are calculated as the power consumption rate times the time that the cleaning apparatus is energized. Gard, Inc.[5] estimates that reverse-air fans and shaker motors use 0.5 hp/1000 ft^2. At an average air-to-cloth ratio of 0.5 m^3/min per m^2 and an operating time of 2 minutes per hour, the yearly (7000 hour) energy usage (kwh) is 1.87 x Q (m^3/min). This is an order of magnitude below that for the fan requirements. Regardless of the type of cleaning, energy demand is considerably less than fan energy requirements, based on a typical fabric filter static pressure drop of 1.5 kPa.

Energy can be reduced by reducing the frequency and intensity of cleaning; but in most cases, this will result in higher average static pressure losses, and thus in higher fan energy demand. In view of the relative magnitudes of energy requirements for cleaning apparatus and fans, less cleaning may be counterproductive. The exception is conversion to a fabric with better cake-release properties, which requires less cleaning without increasing the fan energy demand.

6.1.2.2 Electrostatic Precipitator Subsystems. Four precipitator components use electrical energy:

- Transformer-rectifier sets (T-R) - These convert alternating current at line voltages to high-voltage direct current, and they supply the discharge electrodes that enable particle charging and collection.

- High-voltage insulators - These isolate discharge wire rappers from the high-voltage frame. Heaters are normally advisable to prevent surface condensation, which allows "leakage" of current; insulator heaters can be operated continuously or intermittently.

- Rappers - These remove accumulated solids from collection plates, discharge wires, and gas distribution plates. The rapper system is operated continuously with the activation frequency for an individual rapper normally greater on inlet fields than on outlet fields. Rappers can be powered either electrically or by compressed air.

- Penthouse blowers - These purge the upper housing of the precipitator of vapors that could condense on insulators and cause current "leakage." They are normally operated continuously.

By far the most important energy use is by the T-R sets, which directly control particle charging and collection. Both the peak voltage and the total power input rates influence the level of penetration.[6] There have been trends to increase both over the last 10 years; for example, design power input rates have been increased from a range of 3 to 10 w/(m^3/min) to about 20 to 30 w/(m^3/min).[6,7,8] The T-R set energy demand as a function of design input rates is shown in Figure 6-2.

Comparison of Figures 6-2 and 6-1 clearly indicates the importance of T-R set energy consumption in an electrostatic precipitator system, where the operative mechanism is electrostatic attraction rather than inertial impaction. Impaction systems are normally operated by imposing a gas flow resistance, which is reflected in the fans high-energy demand. No such resistance is necessary in electrostatic precipitator systems.

In actual operation, the power input to a precipitator system is not constant over time. Substantial variability may be introduced by the input mass loadings and the particle characteristics.[6,7,9] High inlet mass concentrations lead to current suppression, particularly in the inlet fields.[7] Likewise an increase in particle resistivity may reduce power input throughout the unit. Power input, as calculated in Equation 6-1, may vary 30 to 50 percent daily, depending on fuel characteristics and process operating conditions.

$$E_{T-R} = \sum_{i=1}^{n} \left(P_{c_i} \times P_{v_i} \times t_i\right)\alpha \qquad \text{(Eq. 6-1)}$$

where E_{T-R} = total energy input to power supplies,

n = number of transformer-rectifier (T-R) sets,

Pc_i = primary current of T-R set i,

Pv_i = primary voltage of T-R set i,

t_i = time T-R set i operational.

α = power factor

Normally, the power input to the electrodes, E_{T-R}, cannot be reduced without an adverse impact on penetration. New power supplies are designed to maximize power input.[6,7]

The power consumption of the rapper system is the sum of the power input to each rapper times the fraction of time that each is activated. Because the rappers normally operate only a small portion of the time, even on inlet fields, the energy consumption is more than an order of magnitude

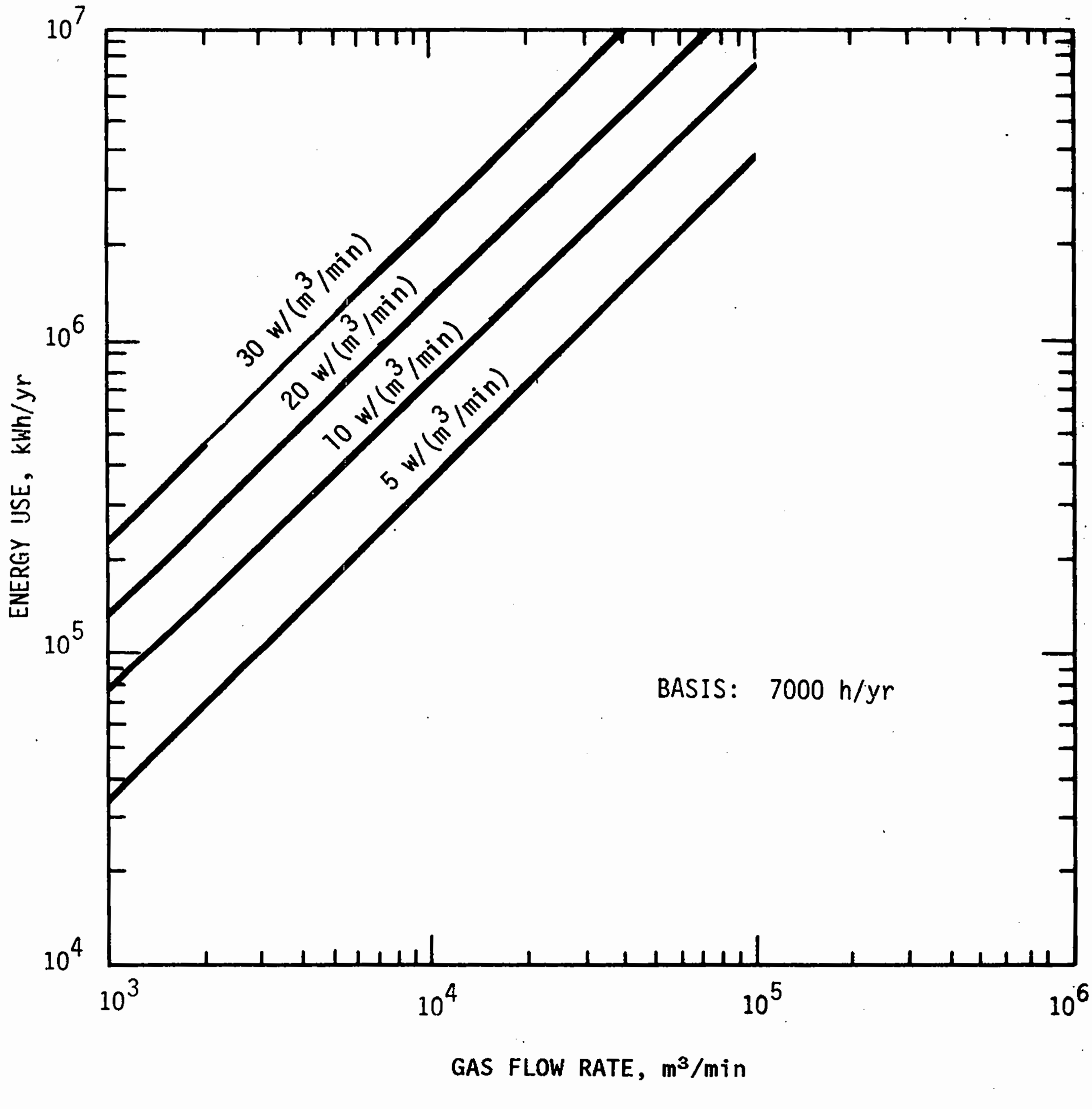


Figure 6-2. Energy required for transformer-rectifier set.

less than that for the T-R sets. Actual energy demand depends on the number of rappers installed, the frequency of activation, and the intensity of operation.

Reduced rapper energy use may offer several secondary benefits. Lower intensity and lower frequency rapping of outlet fields can reduce reentrainment losses in certain installations. Reduced rapping intensity may also lower the probability of electrode misalignment, and thereby reduce future maintenance costs. There is a limit, however, on the extent to which rapper energy savings are feasible. That limit is indicated by simultaneous increases in primary voltages and decreases in secondary currents to the various energized sections. When these changes occur, excessive solids accumulate on collection plates, and precipitator performance begins to deteriorate. The solids buildup can dampen rapper shocks transmitted down the electrodes, and thus further aggravate the solids problem.[6]

High-voltage insulator heaters are operated continuously while the precipitator is operational. Total energy consumption, indicated by curve A of Figure 6-3, depends on the number of heaters and on the rated power input. Despite the continuous operation, the total requirements are relatively minor because of the small number of heaters. This component is a relatively poor candidate for energy conservation because inadequate heating can lead to vapor condensation on insulator surfaces and to voltage reductions and penetration increases.

Energy demand for purge air fans is shown by curve B in Figure 6-3. As with insulator heaters, the requirements depend on the number of blowers used and on their sizes. These fans are typically operated continuously. Potential energy savings are very limited, and are gained at the risk of increased condensation on high-voltage insulators.

6.1.2.3 Wet Scrubber Subsystems. Components using energy in a wet scrubber system are identified below. In most cases, the instrumentation power demand is small relative to the three listed components.

- Pumps - for liquor recirculation, makeup water supply, and purge.
- Agitators - for mixing chemicals for neutralization of scrubbing liquor.

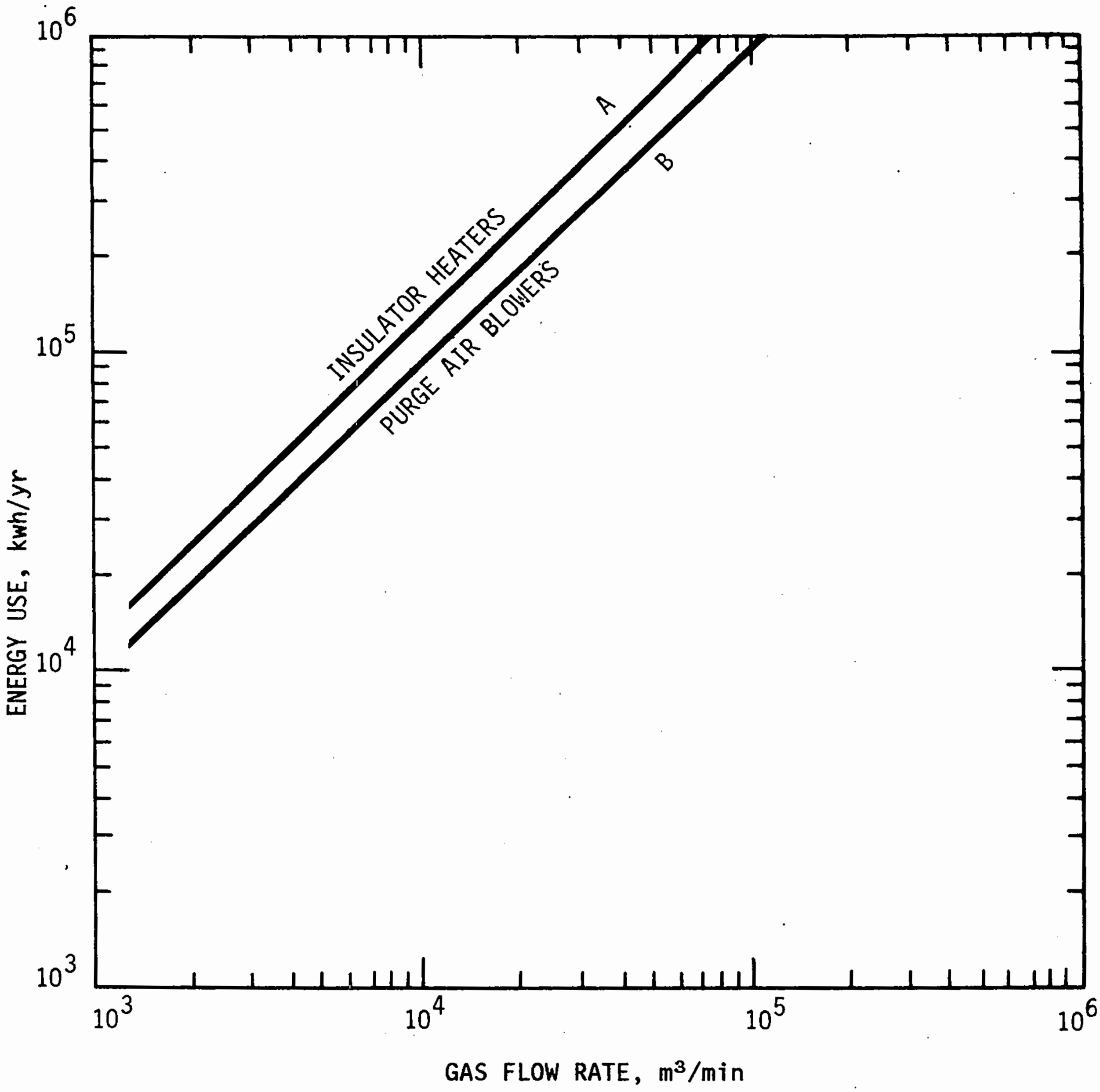


Figure 6-3. Energy required for ESP insulator heaters and purge air fans.

- Reheat - by steam injection or by indirect oil-fired burners for increasing stack temperatures and thus improving the meteorological dispersion characteristics of the effluent.

The energy required to operate pumps is a function of the liquid flow rate and the head.[10] Centrifugal pumps are common in wet scrubber systems. General power requirements for pumps are shown in Figure 6-4; the liquid-to-gas (L/G) ratios apply only to the recirculation pump. The purge and makeup flow rates are generally only 1 to 5 percent of total recirculation flow, and the energy demands are low relative to the recirculation pumps. Energy demand of pumps can be reduced either by reducing recirculation flow or by modifying spray nozzles, but both changes can lead to reduced performance.

Energy demand for stack gas reheat depends primarily on the gas flow rate and on the degree of heating desired. Typically, the scrubbed gas stream is at the adiabatic saturation temperature (normally 50°C) and the necessary reheat is 25° to 50°C. The energy requirements are shown in Figure 6-5.

Stack gas reheating prevents objectionable ground-level concentrations of unremoved pollutants. Means of minimizing reheat costs include increasing stack height, increasing stack gas exit velocities, and eliminating pollutants not treatable in the wet scrubber.[11]

6.1.2.4 <u>Mechanical Collector Subsystems</u>. Mechanical collector subsystems are passive. None of the components within the device use energy. Solids removal equipment is addressed in a later section.

6.1.2.5 <u>Incinerator Subsystems</u>. The incinerator is the only particulate control device directly using fossil fuels. The quantity used depends on gas flow rate, combustion temperature, inlet gas temperature, gas composition (H_2O, CO_2), and heating value of gas stream. Means of calculating energy requirements are discussed in Section 4.6.

Reduced fuel requirements leading to reduced combustion chamber temperatures generally leads to higher particle penetration, especially for particles that are difficult to volatilize. A heat exchanger could prevent reduced temperatures, but poor incinerator performance could cause fouling of the hot side.

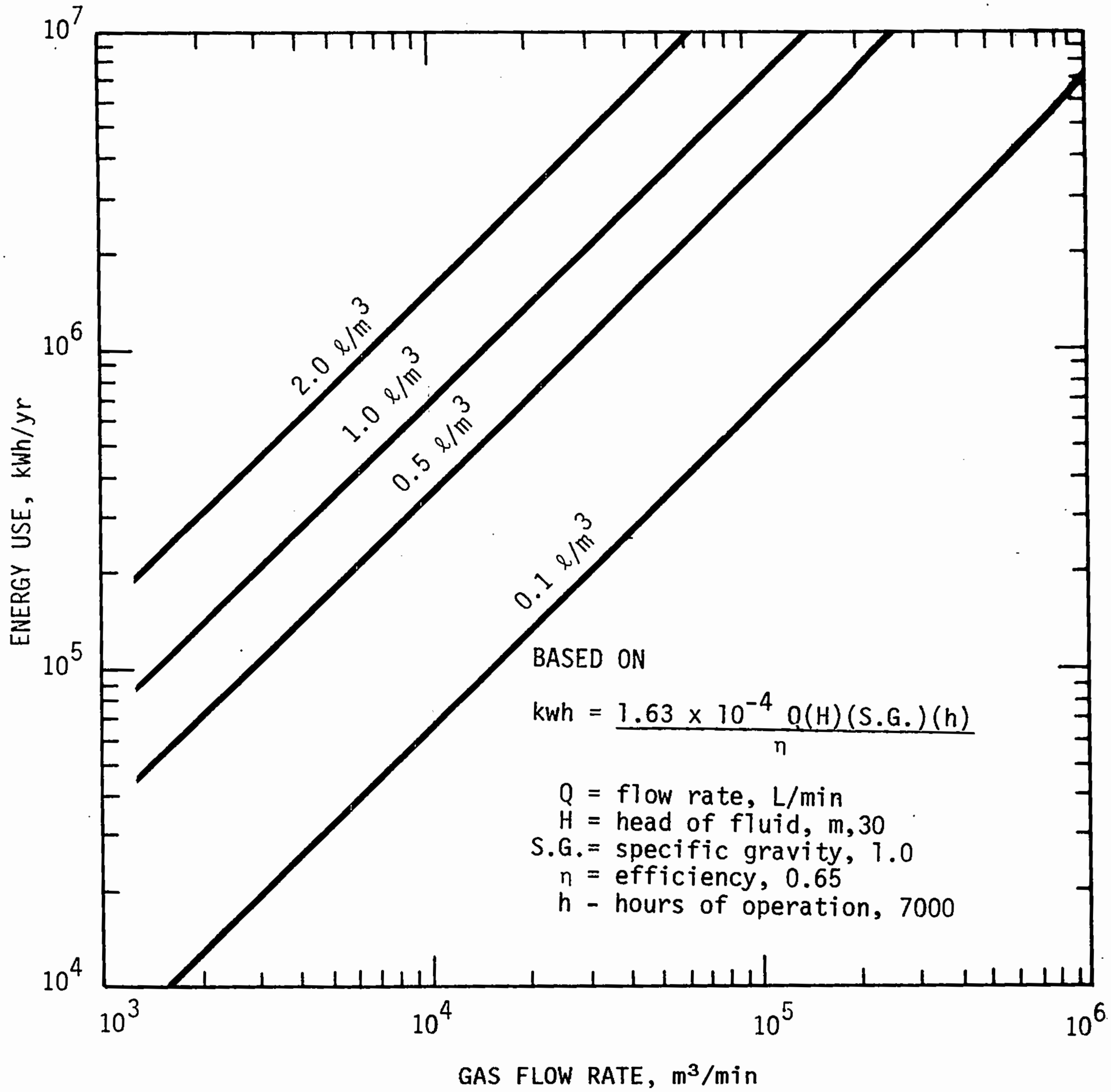


Figure 6-4. Energy required for pumps.

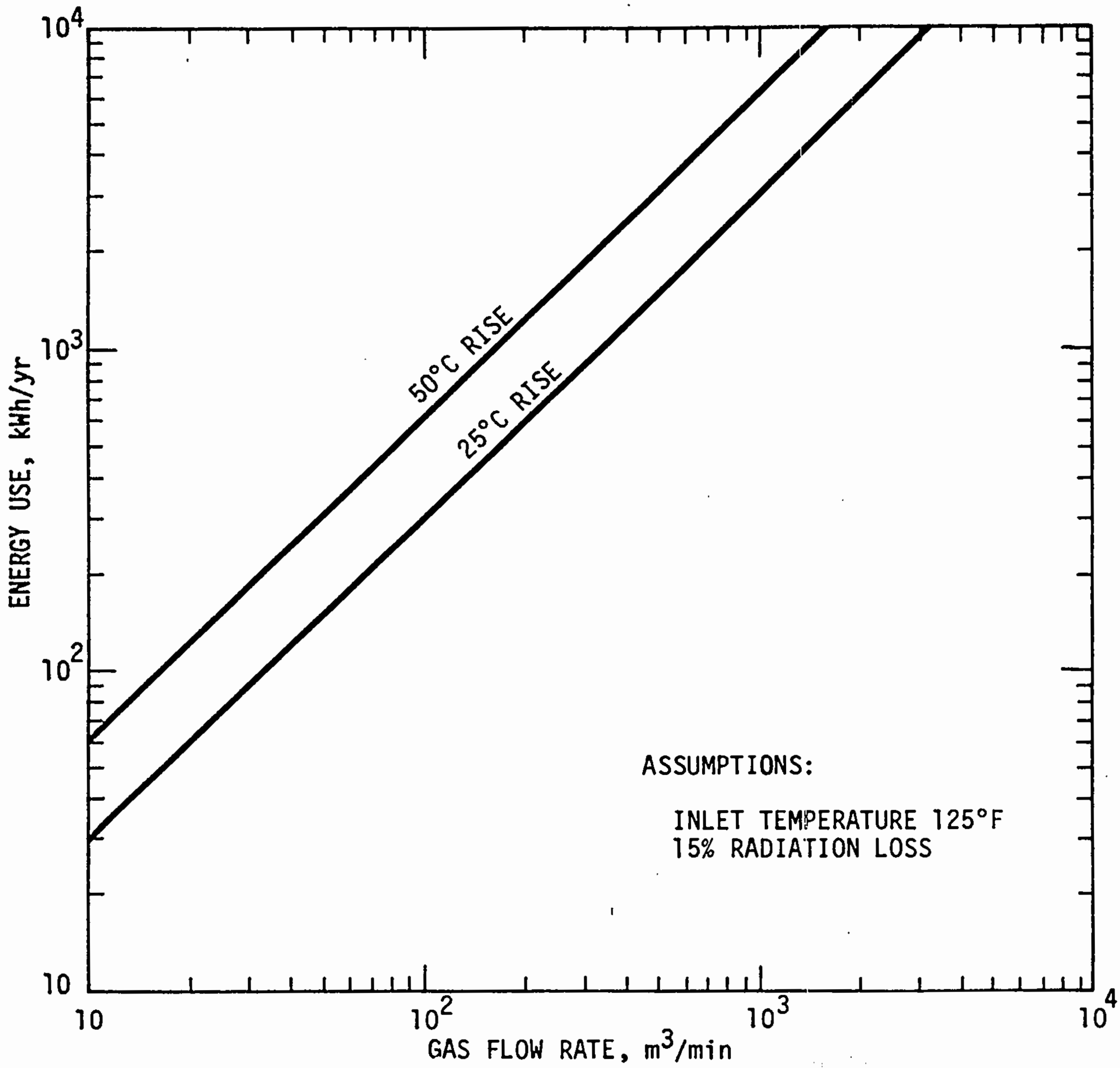


Figure 6-5. Energy required for stack gas reheat.

6.1.3 Hopper Heaters and Vibrators

All dry particulate control devices--including mechanical collectors, fabric filters, and electrostatic precipitators--occasionally require hopper heaters and vibrators to maintain free-flowing discharges of solids. Normally, heaters are used only on larger devices when high-temperature gas streams are being treated. The energy requirements for heaters and vibrators depend on facility size but are independent of control device type.

Heaters and vibrators are normally operated in cycles. Hopper heaters are thermostatically controlled to maintain temperatures above both the acid and the water dewpoints. Vibrators are activated by timers from 1 to 20 times an hour; the energized time period can vary from several seconds to a minute. Energy requirements for heaters and vibrators are a relatively minor part (<10%) of total system energy demand.

Some energy savings may be realized by derating the heaters and reducing the vibrator on-time; such savings, however, are gained at the risk of maintenance problems, and such changes should be carefully planned. Failure to properly discharge solids can lead to misalignment of precipitator electrodes, to fabric deterioration, or to plugging of mechanical collector tubes.

6.1.4 Solids Discharge and Transport

Dry particulate control devices normally incorporate some type of solids discharge valve at the bottom of the hopper and sometimes at screw conveyor transfer points. Solids can be transported by pneumatic systems, pressurized systems, screw conveyors, or drag conveyors. The screw conveyor is normally used with small systems.

For solids transport and discharge equipment, the energy requirements are normally directly proportional to the mass of material. With transport equipment, the distance moved must also be considered.

6.1.5 Ultimate Disposal

Energy is needed to transport solids from a temporary storage site (e.g., a pile or covered pit) to the ultimate disposal site (e.g., landfill). Transport requires energy, but the demand is a relatively small fraction of the overall system energy demand because the solids are in a concentrated, manageable state.

6.1.6 Other Considerations

Recent increases in energy costs have motivated some operators to consider recycling certain treated gas streams to occupied working areas. This may have a substantial benefit on costs of space heating, but this should be adopted cautiously, with full consideration of potential occupational health impacts of control system malfunctions.

6.2 SECONDARY POLLUTANT GENERATION

Particulate control devices have the potential for generating limited quantities of gaseous and particulate air pollutants. Minimizing the generation of these pollutants requires an understanding of their physical and chemical formation mechanisms. Unfortunately, these mechanisms are not fully understood.

6.2.1 Electrostatic Precipitators

Ozone can be formed in negative-corona electrostatic precipitators.[6] Concentrations of 5 to 20 ppm have been reported.[6] Ozone is toxic at concentrations normally encountered in precipitators. Accordingly, strict confined entry procedures should be followed before maintenance is begun.

Ozone generation is only partially understood. Most mechanisms include ionization of molecular oxygen during a spark incident or ionization of molecular oxygen due to absorption of high-energy ultraviolet light emitted by the corona. The former mechanism should be controllable by the reduction of spark rate, which is now possible because of advanced power supplies. The latter mechanism appears more difficult to minimize without affecting precipitator performance. The relative importance of these mechanisms is not known.

There is limited evidence that some sulfur dioxide is oxidized to sulfur trioxide in a negative-corona precipitator.[12] Such substances should either form sulfuric acid aerosols or condense on available particle surfaces. In either case, the generated sulfate would be indistinguishable from that generated in the combustion process. The mode and extent of sulfate formation are not well understood.

6.2.2 Incinerators

Any combustion process can form some nitrogen oxides. Formation mechanism is thought to be reasonably represented by the following reactions, which collectively are referred to as the Zeldovich mechanism.*

1. $N_2 + O \rightarrow NO + N.$
2. $M + O_2 \rightarrow M + 2O$ (M = any third body molecule).
3. $N + O_2 \rightarrow NO + O.$

Reaction 1 has high energy; accordingly, the mechanism is active only at gas temperatures exceeding 1400°C. There is also a strong impact by the oxygen content caused by reaction 6-2. Basically, these reactions are important only within the flame; after the gases leave the combustion zone, the reactions cease, and nitric oxide remains.

Considerable research has been devoted to techniques for suppression of nitrogen oxides formation in coal-, oil- and gas-fired boilers, but very little of this work is directly applicable to burners of the scale and type used for particulate incineration. Available means of reducing nitrogen oxides generation include reduced flame temperatures and reduced excess air.

6.3 LIQUID WASTE MANAGEMENT

The major sources of water pollutants are effluents from scrubbers and from sluicing systems for removing particulate from hoppers. An indirect source is the leachate produced when rain and surface runoff percolate through collected particulate matter that has been disposed of improperly.

6.3.1 Regulatory Requirements

Regulatory requirements that apply to effluents streams from particulate control devices are similar to those that apply to the process being controlled. Effluents from scrubbers, wet electrostatic precipitators, and controls devices using wet sluicing systems are regulated along with other plant sources under the Federal Water Pollution Control Act (Clean Water Act) as "direct dischargers". Direct dischargers are point sources that

* The symbol M refers to any third body molecule.

must conform to numerical limits on various pollutants under Federal effluent guidelines developed on an industry-by-industry basis and based on the Best Practical Control Technology (BPCT). Effluent guidelines based on BPCT and BACT apply to existing sources at the points of discharge from the plant treatment facility. New effluent sources are subject to demonstrated BACT, processes, operating methods, or other alternatives including (where practicable) a standard permitting no discharge of pollutants.

A rigorous discussion of water pollution regulation is beyond the scope of this report. Along with the basic Federal effluent guidelines, other subsections of The Clean Water Act specify control requirements for "priority pollutants" and chemical industry pollutants, which might be subject to rules and regulations under the Toxic Substances Control Act (TSCA) enacted by Congress in 1976.

Most States have EPA-approved National Pollutant Discharge Elimination Systems (NPDES) permit programs. Such programs enable State to issue permits to sources that comply with the requirements of the Clean Water Act, provide for public participation in the permit issuing process, and give EPA, the Corps of Engineers, and other States the opportunity to object to the issuance of a permit. Particulate controls that generate effluent streams should be included on the NPDES permit.

In general, particulate control systems to which effluent regulations apply are subject to the same regulations as the source being controlled. For example, a scrubber controlling a chemical process subject to TSCA might collect toxic air pollutants; the presence of these toxic substances in the scrubber effluent could bring the scrubber under the TSCA guidelines.

6.3.2 Control Techniques

The appropriate treatment for scrubber wastewaters can be selected only after the wastewaters have been completely characterized. Various constituent pollutants of scrubber liquors, such as suspended solids, dissolved solids, toxic metals, biodegradable organics, and acids or caustics require different types of treatment to meet regulatory discharge requirements.

6.3.2.1 Primary Treatment. Suspended solids, found in nearly all scrubber wastewaters, are removed by sedimentation (commonly referred to as primary treatment). Sedimentation is accomplished by allowing the wastewater to flow slowly through a large basin or pond so that suspended particles collect by gravity. Clarifier basins (Figure 6-6) use automatic mechanical devices to continuously remove accumulated sludge, whereas settling pond sludge is removed in a batch fashion. Increasing the size of a sedimentation basin or pond increases the wastewater detention time, and thus improves sedimentation efficiency. Sedimentation of very small particles can be improved by adding flocculants to the wastewater prior to sedimentation to cause the fine particles to agglomerate into larger, more easily separated particles.[13,14]

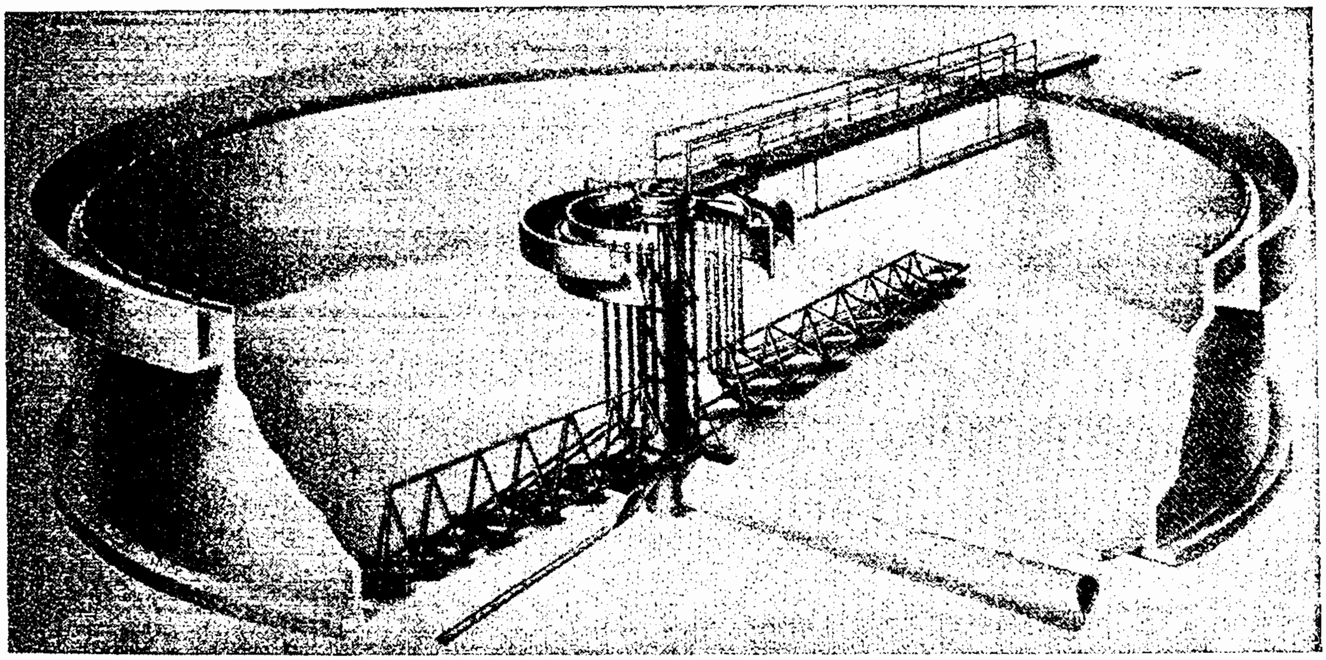


Figure 6-6. Sedimentation tank or "clarifier."[13]

6.3.2.2 Secondary Treatment. Some scrubber wastewaters may contain biodegradable organic compounds which, if untreated, will exert a biological oxygen demand (BOD) on receiving waters. Such organic compounds can be found in scrubber wastewaters at pulp and paper plants, wood products plants, food processing plants, and other industries. Such BOD-causing wastes must receive biological treatment, commonly referred to as secondary treatment, prior to discharge. Failure to treat BOD-causing wastes can cause the growth of aerobic bacteria in receiving waters, the accompanying depletion of dissolved oxygen, the death of naturally occurring organisms in the water, and the growth of anaerobic odor-causing bacteria.

Secondary treatment is accomplished by allowing aerobic microorganisms to biologically degrade the BOD-causing organic compounds before their release into surface waters. This biological activity requires a constant influx of oxygen into the wastewater and sufficient detention time. Secondary treatment is usually accomplished by oxidation ponds, trickling filters, or activated sludge units. Additional sedimentation must follow trickling filters and activated sludge units to remove suspended bacteria from the wastewater.[13,15]

6.3.2.3 Tertiary Treatment. Although primary and secondary treatments may remove most suspended solids and BOD from wastewaters, but advanced wastewater treatment, sometimes referred to as tertiary treatment, are needed for pollutants such as nitrogen, phosphorus, inorganic acids, nonbiodegradable organics, and heavy metals.

In many particulate scrubbers, especially those at phosphate rock mines and at fertilizer plants, the liquors contain phosphorus and nitrogen and excessive discharge of phosphorus and nitrogen disrupts the ecological balance in lakes and streams by stimulating profuse growth of algae. Phosphorus is removed by adding coagulants such as alum, lime, and ferric chloride to convert the phosphorus to an insoluable form.[13] These additions cause the phosphorus to precipitate, coagulate, and settle from the wastewater. Coagulants for phosphorus removal can be added before primary treatment, before secondary treatment (if is required), or as a separate tertiary treatment.

Three major processes are used to remove nitrogen from wastewaters. Biological nitrification-denitrification is the aerobic biological conversion of nitrogenous matter into nitrates (nitrification), followed by anaerobic biological conversion of nitrates into nitrogen gas for release to the atmosphere (denitrification); both steps resemble the activated sludge process in secondary treatment, but different microorganism colonies develop in the vessels, and denitrification occurs without oxygen. A second method is ammonia stripping by raising the pH of the wastewater and passing the water through a stripping tower, from which gaseous ammonia is released to the atmosphere; scrubbing liquor nitrogen must be in the form of ammonium ions for stripping to be effective. The third method is selective ion exchange, which resembles a home water softener; ammonium ions in solution are exchanged for sodium or calcium ions displaced from an insoluble exchange material.[13]

Scrubbing liquors from cast iron cupolas, certain chemical processes, incinerators, steel mills, and many other industries can contain soluble organics such as phenols and benzene, or colloidal oils, which are resistant to biological breakdown during secondary treatment. These impurities, often referred to as "refractory organics," can be responsible for unwanted colors or tastes in water, and many are suspected carcinogens. Refractory organics are generally removed from wastewater by carbon adsorption: wastewater is passed through a bed of granular activated carbon, where the organics are adsorbed onto the carbon surfaces until the carbon becomes saturated and has to be regenerated or replaced.[13]

In scrubber wastewaters, toxic heavy metals such as chromium from metal plating operations, or lead, mercury, and copper require special treatment. Soluble metals can be removed by one of two methods. One is high-pH lime coagulation, which is especially attractive if phosphorus must also be removed; the other method is selective ion exchange, which is especially attractive if nitrogen must also be removed.[13,15]

Some wastewaters contain significant colloidal material even after coagulation-sedimentation in primary or secondary treatment. If this colloidal material is not suitable for discharge because of high turbidity or its chemical nature, filtration can be accomplished by passing the wastewater through a granular bed of sand or other small particles. As the filter becomes plugged, it can be cleaned by briefly reversing the flow ("backwashing") at a high flow rate. Backwash wastewaters, usually less than 5 percent of total flow, must be recycled to the wastewater treatment plant.[13]

6.3.2.4 Other Treatment Considerations. Several other points must be considered when selecting a treatment or wastewater from a scrubber. Should scrubber wastewaters be combined with other plant wastewater streams or treated separately. If the wastewater contains toxic materials or has extreme pH values, the routing of scrubber effluents directly into plant (or municipal) treatment facilities can "poison" biological treatment processes. Scrubber liquors which contain neither biodegradeable organics nor toxic materials and which require no secondary or tertiary treatment, can be treated most economically by primary treatment separate from plant treatment facilities. Other liquors can be routed directly to combined treatment facilities, or they can be treated for pH control before being routed to combined facilities. If scrubbing liquors are changed in a batch fashion instead of by continuous blowdown, flow equalization facilities may be required to prevent overload of plant treatment facilities.

6.3.2.5 Sludge Handling. Purifying scrubber wastewaters can lead to another problem--sludge handling. Sludges withdrawn from treatment processes are still largely water (often more than 90%). Thus, sludge treatment must separate solids from the large amounts of water, return the separated water to the wastewater plant for reprocessing, and dispose of the separated solids in an environmentally appropriate manner according to applicable regulations (Section 6.4).

Several processes are available for the dewatering of sludge. One or more of these processes may be required to properly dewater a particular sludge. A common first step in dewatering is sludge conditioning, where coagulants such as ferric chloride, lime, or organic polymers are added to more easily separate sludge solids from water. After conditioning, sludges are often thickened by gravity settling in vessels similar to wastewater clarifiers to reduce sludge volume by a factor of 2 or more. Biological sludges (i.e., from secondary treatment clarifiers) often require sludge "stabilization" to breakdown organic solids so that they are more stable (less odorous and less putrescible). Stabilization can be accomplished in anaerobic and aerobic biological sludge digesters.[13]

Many thickened or stabilized sludges receive final dewatering by vacuum filtration (Figure 6-7). A vacuum filter consists of a cylindrical drum covered with a filtering material or fabric partially submerged in a vat of conditioned sludge. A vacuum is applied to the inside of the drum to extract the water, leaving the solids or "filter cake" on the filter medium. A blade scrapes the filter cake from the filter medium as the drum rotates.[13] Some sludges are filtered more readily if the filter medium is precoated with various dusts, usually applied daily. Another method of final dewatering is drying on sandbeds. After dewatering by vacuum filtration or sand drying, sludges are either incinerated or landfilled, depending on their properties.

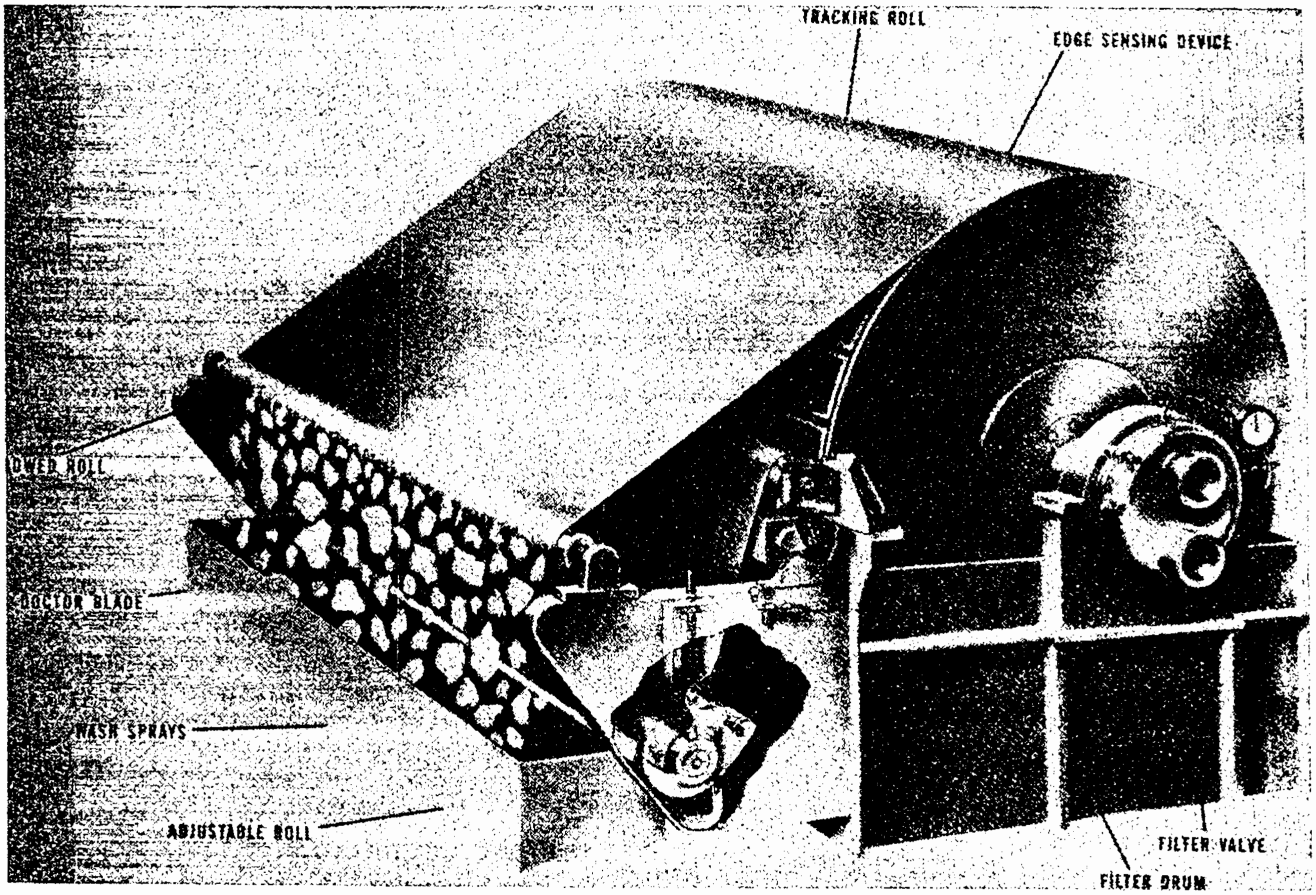


Figure 6-7. Vacuum filter.[13]

6.4 SOLID WASTE MANAGEMENT

Substantial quantities of solids and sludges are collected in particulate control systems. Ideally, these materials are recycled to partially offset control costs and to avoid disposal costs. Unfortunately, the physical and chemical characteristics of these materials frequently render them noncompetitive in the very limited markets presently available. This section describes the general chemical and physical properties that determine recycle potential and disposal requirements. Information specific to particular industries and processes is available in the Background Information

Documents for the Standards of Performance for New Sources and in the Industrial Process Profiles for Environmental Use.

6.4.1 Regulatory Requirements

The major Federal regulations affecting solid waste disposal were established under the Resource Conservation and Recovery Act (RCRA). Under this Act, the generation, treatment, and disposal of solid (hazardous) wastes are strictly regulated. In most situations, a permit is required by a generator (e.g., a facility that generates scrubber sludge), regardless of whether the generator disposes of the hazardous material on or off site. In addition, the generator, transporter, and the disposal facility must complete a manifest form every time hazardous waste is shipped, so that the waste can be tracked from "cradle to grave" and to eliminate illegal disposal of hazardous wastes.

When waste from a wet scrubber or a wet electrostatic precipitator is disposed of in an underground injection well, a permit must be obtained, according to the Safe Drinking Water Act of 1974. The Act established a national program to prevent underground injections that endanger drinking water sources.

6.4.2 Waste Recycle

Properties of accumulated materials determine the extent to which reuse is economically attractive. A partial list of important physical and chemical properties is provided below:

Physical properties
- Loss on ignition
- Carbon content
- Particle size distribution
- Moisture content
- Pozzolanic activity

Chemical properties
- pH
- Soluble fraction
- Trace element composition

"Loss on ignition" and "carbon content" measure similar properties, in that carbonaceous materials normally constitute most of the combustible fraction of collected solids. Loss on ignition of fly ash from a pulverized-coal-fired boiler normally ranges from 0.2 to 17 percent by weight. The normally acceptable range is 6 to 12 percent by weight if fly ash is to be used as a filler in portland concrete and asphalt concrete; this strict range limits the use of fly ash as a filler. In 1972, only 11 percent by weight of the fly ash from pulverized coal was used as a filler. Since the carbon content of fly ash from a stoker-fired boiler is typically 25 percent or more, this material is unsuitable for use in concrete.

Particle size distribution is important. Excessive fines measured by the minus-325 mesh fraction generally inhibit use. For use as filler in cement, the fine fraction should not exceed 12 percent by weight; however, the reported values for ash from pulverized-coal-fired boilers are 7 to 60 percent. The fines of any solids collected in particulate control devices depend on the effectiveness of agglomeration in the hopper and in solids transport equipment. (Agglomeration is caused by condensation of moisture and inorganic vapors on particle surfaces during cooling.) Excessive fines renders any use unattractive because of the fugitive dust created during materials handling.

Moisture content influences recycle potential in a variety of ways. Low moisture content (<3.5% by weight) increases potential dusting problems, as discussed above, and increases the explosive potential of dusts. High moisture content (>20-40% by weight) leads to materials-handling problems because the solids begin to agglomerate and to cake, and may have an adverse impact on the process fuel requirements. For these reasons, the solids collected in wet scrubbers are rarely recycled.

The chemical composition of the dry particulate catch can affect use. For example, the alkali content of portland cement kiln dust must be below the limits stated in product specifications. Often it is possible to use solids from the inlet fields of the precipitator, but not from subsequent fields, which remove the majority of entrained alkali particles.

The potential for groundwater contamination from waste disposal sites depends partially on the quantity of water-soluble compounds that could leach out. Fly ash from pulverized-coal-fired boilers contains approximately 1 to 5 percent by weight water-soluble compounds. The major dissolved compounds include sulfates, chlorides, and calcium ions; arsenic, mercury, and cadmium compounds are moderately soluble. The residue from municipal incinerator collectors can have water-soluble fractions as high as 15 percent by weight.

6.4.3 Waste Disposal

Waste characteristics and regulatory requirements must be fully considered in the selection of a disposal technique. Possible disposal techniques include (1) placement in lined or unlined ponds, (2) placement in a landfill, either as-received or after fixation treatment, and (3) deep well injection.

Unlined ponds are satisfactory when leachate from the waste liquors or slurries can be controlled either by special pond construction (e.e., underdrainage systems) or by soil permeability properties. Various techniques are available for analysis of pond leakage include soil resistivity monitoring networks and underdrainage system inspection sumps.

Among the liner materials available to improve leachate security in ponds are various synthetic materials and clays. Flexible liners have an estimated life of 20 to 25 years; nonflexible liners are more permanent. Liner thicknesses range from 0.025 to 0.075 cm for synthetic materials such as polyethylene and polyvinylchloride, from 30 to 40 cm for clays, and approximately 15 cm for asphalt and concrete. Cost of the lining must be weighed against the security offered by thicker liners.

Dry or dewatered material can be disposed of in a landfill. The stability of the fill material and the groundwater contamination potential should be considered. For example, water runoff should be channeled around these sites to minimize leaking of soluble compounds. Soil characteristics and groundwater levels should be determined to avoid improper landfill location.

Treatment of the waste may be necessary to reduce potential landfill problems. Scrubber sludges can be treated chemically to "fix" the material into a physically stable, leach-resistant matrix. Wastes can also be filtered to reduce moisture content.

Deep well injection generally is not economically attractive for disposal of the quanitities and types of wastes discharged from particulate control devices.

6.5 NOISE MANAGEMENT

Noise from particulate controls is generated by fans, ESP rapping, wet scrubber pumps, and solids transportation systems. The noise levels from most of these sources are usually negligible compared with noise from the other plant sources. Objectionable noise levels attributable to particulate control systems are most frequently generated by fans. If there is a need to decrease the noise level from fans, the rotational speed should be reduced and the additional capacity shifted to a parallel fan. Sound insulation can also be used for fans as well for other components, such as ESP rappers.

6.6 RADIATION CONTROL

Radiation sources associated with particulate controls are limited to nuclear level indicators for hoppers. Radiation from such indicators is usually minor and not sufficient to warrant the requirement that plant personnel wear nuclear badge detectors or dosimeters. These potential radiation exposure areas, however, must be marked in accordance with Federal regulations. Periodic checks could be made for radiation leakage with a Geiger-Mueller detector.

REFERENCES

1. American Conference of Governmental Industrial Hygienists. Industrial Ventilation Manual, 16th edition. Lansing, Michigan, 1980.

2. Jorgensen, R., editor. Fan Engineering 7th edition, Buffalo Forge Company, Seventh Edition, 1970.

3. Pollak, R. Selecting Fans and Blowers. Chemical Engineering, 80(3), January 23, 1973.

4. Heath, C. Energy Analyses. National Asphalt Paving Association. Publication 52, October 1978.

5. Neveril, R. B. Capital and Operating Costs of Selected Air Pollution Control Systems. EPA-450/5-80-002. December 1978.

6. Katz, J. The Art of Electrostatic Precipitation. S & S Printing Company, Pittsburgh, Pennsylvania, 1979.

7. Szabo, M., and R. W. Gerstle. Operation and Maintenance of Particulate Control Devices in Kraft Pulp Mill and Crushed Stone Industries. EPA-600/2-78-210, 1978.

8. Szabo, M., and Y. Shah. Inspection Manual for Evaluation of Electrostatic Precipitator Performance. EPA-340/1-78-007, February 1979.

9. White, H. Electrostatic Precipitation of Fly Ash. Air Pollution Control Association, Pittsburgh, Pennsylvania, July 1977.

10. Karassik, I., and W. Krutzsch. Centrifugal and Axial Pumps. In: Standard Handbook for Mechanical Engineers, 7th edition. McGraw-Hill Book Company, New York, N.Y., 1967.

11. PEDCo Environmental Specialists, Inc. Flue Gas Desulfurization Process Cost Assessment. Draft report for U.S. Environmental Protection Agency under contract no. 68-01-3150.

12. Brown, W. R. and E. E. Stone. Sulfur Dioxide Conversion under Corona Discharge Catalysis. U.S. Public Health Services contract no. PH-86-67-2, March 1965.

13. Environmental Pollution Control Alternatives: Municipal Wastewater. U.S. EPA Technology Transfer. EPA-625/5-76-012, 1976.

14. Metcalf and Eddy, Inc. Wastewater Engineering. McGraw-Hill Book Company, New York, N.Y., 1972.

15. Weber, Jr., W. J. Physiochemical Processes for Water Quality Control. Wiley-Interscience, New York, N.Y., 1972.

SECTION 7

COSTS OF PARTICULATE CONTROL EQUIPMENT AND FUGITIVE EMISSION CONTROL TECHNIQUES

The selection of a particulate control technique depends upon many factors, such as degree of required emission reduction, gas stream characteristics, and cost. This section deals with the costs of purchasing, installing, and operating various particulate control devices and techniques. The particulate control equipment addressed includes electrostatic precipitators, fabric filters, mechanical collectors, incinerators, and scrubbers. The fugitive emissions control techniques evaluated include wet suppression and stabilization.

The total cost of a particulate control system is influenced by many factors. The cost of the control and auxiliary devices can be highly variable in view of the many options that may be applicable. Even when the type of equipment is selected, different materials of construction and penetration levels affect costs to a large extent. Auxiliary instrumentation useful to improve reliability and to reduce maintenance can also have a great effect on cost.

Retrofit applications can result in installation costs that greatly exceed the costs of a new installation. Space restrictions, difficult tie-ins, and outdated process equipment can cause added expense.

In addition to the collection costs of particulate, a cost estimate of residue disposition must be made. Collected solids or sludges may constitute a significant expense for disposal, or, when the particulate consists of recovered product, a valuable credit. Facilities for treatment of wet scrubber sludges may be necessary.

Labor expense affects both capital and annualized costs in the form of installation, operation, and maintenance. This expense also carries with it sizable overhead costs.

Given compliance with other limiting factors, cost-effectiveness often provides a primary criterion for choosing among various pollution control alternatives. Cost-effectiveness is a measure of the total cost of a specified reduction in emissions. Computation of cost-effectiveness must take into account all annualized costs including direct operating costs and capital charges.

7.1 PARTICULATE CONTROL EQUIPMENT COST ANALYSIS

7.1.1 Capital Costs

Capital costs of a particulate control system include the cost of the purchased equipment; i.e., the control device and its accessories, and all installation costs. Installation costs are divided into direct costs such as those for foundations, piping, and painting, and indirect costs such as those for engineering and supervision. Equipment costs generally form the basis for estimating total capital costs for a particulate control system.

There are several methods for estimating the total capital costs of particulate removal systems. The accuracy of any method is directly related to the amount and detail of the information available. Simple cost-estimating methods dependent solely on the type of unit and its capacity are the least accurate; methods requiring preliminary engineering drawings and specifications and detailed energy balances are generally the most accurate. A discussion of several estimating techniques follows.

An order-of-magnitude estimate of total capital costs is based on the average cost for equipment of a particular type and capacity. For air pollution control facilities, these parameters are usually determined by gas volume to be treated and the desired pollutant removal efficiency. The range of average capital costs can be very wide; thus this simple method of estimating costs is the least accurate.

Another method of estimating total capital costs is that in which factors are applied to the cost of the major pieces of equipment as a means of estimating the remainder of the costs. Experience gained from previous projects (historical data) provides the multiplication factors used in this method. There are several variations of the factor method, each requiring different input and producing different degrees of accuracy. The Lang, Chilton, and Guthrie procedures are three variations that were developed for use in estimating the cost of chemical plant construction. The method of cost estimation used to obtain the cost curves presented in Section 7.3 is a variation of the Lang method that EPA has developed for application to air pollution control systems. This system is fully explained in Reference 1.

When total capital cost data are available for a system of similar design but of different capacity from that required for a particular application, a scaled estimate can be utilized. Scaled estimates are usually derived by use of the following equation:

$$E_2 = E_1 \left(\frac{r_2}{r_1}\right)^n \qquad \text{(Eq. 7-1)}$$

where

E_2 = cost of desired control device

E_1 = cost of scaled control device

r_2 = capacity of desired control device

r_1 = capacity of scaled control device

n = exponent relation

This equation specifies that a log-log plot of capacity versus cost should be a straight line with slope n. With respect to equipment costs, n has been shown to average 0.6 and is referred to as the six-tenths factor. Although the six-tenths factor is most accurate when applied to a single piece of equipment, it can also be used for estimating complete system costs. Its use should be limited, however, to cases where no other costs are readily available for the desired control device.

The most accurate methods of capital costs estimation require complete drawings and specifications, material and energy balances, site surveys, and other engineering effort. The extent of the data obtained will determine the accuracy provided by the estimate. Accuracy of ±5 percent is possible if sufficient information is available. In contrast, however, cost spreads of 20 percent are sometimes encountered in formal bids as a result of market conditions, interpretation of plans and specifications, subjective assessment of installation difficulties, and error.

7.1.2 Annualized Costs

Annualized costs of a particulate control system include direct costs such as operating labor and materials, maintenance, replacement parts, utilities, and the costs of particulate disposal; also included are indirect costs such as overhead, insurance, taxes, and capital recovery, and credits derived from recovery of particulate product.

Direct annualized cost estimates are obtained by applying unit costs of utilities, labor, and materials to the estimated requirements for these items. Indirect costs are derived generally by combining percentages of the capital costs with a percentage of labor charges for operation and maintenance and capital recovery costs. Capital recovery costs depend on interest rates, the useful life of the equipment, and the equipment's salvage value, if any.

7.1.3 Other Cost Considerations

Certain aspects of cost analysis are always affected by some degree of uncertainty. When new technology is included, an adequate data base may not be developed for proper evaluation. Differences in the expected service lives of alternative systems may require appropriate adjustments in cost comparison. Changes in labor rates, material costs, or fuel costs also may affect the accuracy of cost analysis.

Inflation is always an important consideration, since inflation rates are subject to change, reflecting other economic factors. Cost indexes are available to aid in adjusting past costs into current dollars.

The cost of retrofit applications can be difficult to assess by use of typical cost analyses. Additional engineering input is important to account properly for potential additional expenses for such items as site preparation, overtime labor, utility system modifications, space restrictions, and lost production. By the methods described in Reference 1, retrofit cost curves have been developed and are compared with those for grass-roots installations in Section 7.3.

7.2 METHODOLOGY FOR ANALYZING COST OF PARTICULATE CONTROL SYSTEMS

The method of cost analysis used in the analyses presented here is identical to that used in Reference 1, which should be referred to for a detailed explanation of cost analysis of air pollution control systems. A brief explanation of the method is included in this section.

7.2.1 Capital Costs

Purchased equipment costs provide the basis for estimating the remaining capital costs; i.e., direct and indirect installation costs, for particulate control systems. The purchased equipment costs include the price of the control device, auxiliary equipment, instruments and controls, taxes, and freight. Although the cost of a device and its auxiliaries may be fairly standard for a particular size and type, the costs of instrumentation and freight can vary considerably, depending upon the type and location of application.

Installation costs are derived by applying the applicable cost factors shown in Table 7-1. Many of the individual items in the installation categories, direct and indirect, are subject to site-specific adjustment. In the direct cost category, erection and handling, site preparation, and facilities and buildings are subject to adjustment. Purchased equipment cost does not, however, directly determine the work needed in preparing the site of erecting buildings. These cost items are more dependent upon the nature of the facility and whether the application is new or retrofit. The costs of foundations and supports, electrical work, piping, insulation, and paintings are all generally proportional to the purchased equipment cost, and adjustments are not deemed necessary.

Many indirect costs can vary considerably. Engineering and supervision, construction and field expenses, and construction fee depend to some degree on site-specific conditions and therefore require appropriate adjustment.

Table 7-2 indicates that total direct and indirect installation cost factors can range widely. The importance of knowledge of the specific application is clear; use of the appropriate cost adjustments can be the most important aspect of this cost analysis.

Table 7-1. AVERAGE[a] COST FACTORS FOR ESTIMATING CAPITAL COSTS[1]

Cost factors	Electrostatic Precipitator	Wet Scrubber	Fabric filter	Incinerator
Direct costs				
1. Purchased equipment costs				
a) Control device				
b) Auxiliary equipment	0.82	0.82	0.82	0.82
c) Instruments and controls	0.10	0.10	0.10	0.10
d) Taxes	0.03	0.03	0.03	0.03
e) Freight	0.05	0.05	0.05	0.05
Subtotal	1.00	1.00	1.00	1.00
2. Installation direct costs				
a) Foundations and supports	0.04	0.06	0.04	0.08
b) Erection and handling	0.50	0.40	0.50	0.14
c) Electrical	0.08	0.01	0.08	0.04
d) Piping	0.01	0.05	0.01	0.02
e) Insulation	0.02	0.03	0.07	0.01
f) Painting	0.02	0.01	0.02	0.01
g) Site preparation	b	b	b	b
h) Facilities and buildings	b	b	b	b
Subtotal	1.67	1.56	1.72	1.30
Indirect costs				
3. Installation indirect costs				
a) Engineering and supervision	0.20	0.10	0.10	0.10
b) Construction and field expense	0.20	0.10	0.20	0.05
c) Construction fee	0.10	0.10	0.10	0.10
d) Startup	0.01	0.01	0.01	0.02
e) Performance test	0.01	0.01	0.01	0.01
f) Model study	0.02	0	0	0
g) Contingencies	0.03	0.03	0.03	0.03
Total[c]	2.24	1.91	2.17	1.61

[a] These average factors may require adjustments for individual estimates.

[b] As required.

[c] The relative costs for items 2(g) and 2(h) must be added to these average totals.

Table 7-2. COST ADJUSTMENT FACTORS FOR EMISSION CONTROL SYSTEMS[1]

Adjustment factor	Cost adjustment factor
Instrumentation	
1. Simple, continuous manually operated	0.5 to 1.0
2. Intermittent operation, modulating flow with emissions monitoring instrumentation	1.0 to 1.5
3. Hazardous operation with explosive gases and safety backups	3
Freight	
1. Major metropolitan areas in continental U.S.	0.2 to 1.0
2. Remote areas in continental U.S.	1.5
3. Alaska, Hawaii, and foreign	2
Handling and erection	
1. Assembly included in delivered cost with supports, base, skids included. Small to moderate size equipment	0.2 to 0.5
2. Equipment supplied in modules, compact area site with ducts and piping less than 70 meters. Moderate-size system	1
3. Large system, scattered equipment with long runs. Equipment requires fabrication at site with extensive welding and erection	1.0 to 1.5
4. Retrofit of existing system; includes removal of existing equipment and renovation of site. Moderate to large system	2
Site preparation	
1. Within battery limits of existing plant; includes minimum effort to clear, grub, and level	0
2. Outside battery limits; extensive leveling and removal of existing structures; includes land survey and study	1
3. Requires extensive excavation and land ballast and leveling. May require dewatering and pilings	2
Facilities and buildings	
1. Outdoor units, utilities at site	0
2. Outdoor units with some weather enclosures. Requires utilities brought to site, access roads, fencing, and minimum lighting	1
3. Requires building with heating and cooling, sanitation facilities, with shops and office. May include railroad sidings, truck depot with parking area	2
Engineering and supervision	
1. Small-capacity standard equipment, duplication of typical system, turnkey quote	0.5
2. Custom equipment, automated controls	1 to 2
3. New process or prototype equipment, large system	3
Construction and field expenses	
1. Small-capacity systems	0.5
2. Medium-capacity systems	1
3. Large-capacity systems	1.5
Construction fee	
1. Turnkey project, erection and installation included in equipment cost	0.5
2. Single contractor for total installation	1
3. Multiple contractors with A&E firm's supervision	2
Contingency	
1. Firm process	1
2. Prototype or experimental process subject to change	3.3 to 5
3. Guarantee of efficiencies and operating specifications	5 to 10

7.2.2 Annualized Costs

Annualized costs are categorized in Table 7-3, which also gives example cost factors. Direct operating costs are such that rates for labor, material, and utilities can be applied to estimates of requirements for these items. The rates can be obtained as average figures from sources such as the Bureau of Labor Statistics and the Federal Energy Regulatory Commission, or rates for specific areas can be obtained from actual consumers.

The requirements for operating labor and supervision depend on system variables, such as degree of automation, and operational variables, such as continuity of operation and number of shifts. Maintenance requirements depend upon the nature of the gas stream; e.g., corrosiveness or abrasiveness, construction materials, and system size and type. Labor and maintenance costs can be estimated from information presented in Reference 1.

Utility requirements are derived by use of the following formulas:

Fans

$$kWh = \frac{8.3\ Q\ (\Delta p)(SG)(h)}{10^4\ \eta} \qquad \text{(Eq. 7-2)}$$

where:

kWh = energy usage in kilowatt-hours

Q = actual volumetric flow rate, m^3/s

Δp = pressure loss, Pascals

η = efficiency, usually 60 to 70 percent

h = hours of operation

SG = specific gravity as compared to air

Pumps

$$kWh = \frac{9.80\ Q(H)(SG)(h)}{\eta} \qquad \text{(Eq. 7-3)}$$

where:

TABLE 7-3. EXAMPLE FACTORS FOR ANNUALIZED COSTS[1]

Direct operating costs	Cost factor[a]
Operating labor	
Operator	\$7.87/man-hour
Supervisor	15% of operator
Operating materials	As required
Maintenance	
Labor	\$8.66/man-hour
Material	100% of maintenance labor
Replacement parts	As required
Utilities	
Electricity	\$0.012/MJ
Fuel oil	\$125/m^3
Natural gas	\$0.071/m^3
Plant water	\$0.67/m^3
Water treatment and cooling water	\$0.27/m^3
Steam	\$11.7/Mg
Compressed air	\$0.0007/m^3
Waste disposal	\$6-12/Mg
Indirect operating costs	
Overhead	80% of operating labor and maintenance labor
Property tax	1% of capital costs
Insurance	1% of capital costs
Administration	2% of capital costs
Capital recovery cost	0.16275 (as an example of 10% and an equipment life of 10 years)
Credits	
Recovered product	As required

[a] All costs are in December 1977 dollars.

kWh = energy usage in kilowatt-hours

h = hours of operation

Q = flow rate, m^3/s

H = head of fluid, m

SG = specific gravity

η = efficiency, usually 60 to 70 percent

Waste disposal costs do not always apply; when products are recovered, such material constitutes a credit.

Indirect operating costs are based on both direct operating costs and capital costs. Overhead costs are a straight percentage of wages and salaries; they cover expenses for such items as fringe benefits and cafeterias.

Capital recovery costs are derived by use of the following equation:

$$\text{Capital recovery cost} = \text{capital costs} \times \frac{i(1 + i)^n}{(1 + i)^n - 1} \qquad \text{(Eq. 7-4)}$$

where:

i = annual interest rate

n = capital recovery period, years

Specific information regarding overhead cost factors and equipment lives can be obtained from Reference 1.

7.3 COST CURVES FOR VARIOUS PARTICULATE CONTROL SYSTEMS

This section presents cost data for several particulate control systems. Three cost curves are given for each type of control technique, representing purchased equipment costs, total capital costs, and annualized costs. All costs are estimated from information contained in Reference 1 and updated to January 1980 dollars. The accuracy of any curve relative to a specific application depends upon the similarities between the assumptions used in the example and the conditions under which the system will actually be used. The curves should not be relied upon, however, to provide better than ±50 percent accuracy. For more precise estimates, it is recommended that the reader apply the cost analysis method described earlier and explained in detail in Reference 1.

7.3.1 Equipment Costs

Figure 7-1 through 7-5 show the estimated purchased costs, F.O.B. factory, for five state-of-the-art particulate control device categories: (1) electrostatic precipitators, (2) fabric filters, (3) mechanical collectors (cyclones), (4) incinerators, and (5) venturi scrubbers. The curves represent flange-to-flange costs and generally include internal electricals and controls. Instrumentation is not included because it is usually provided as an optional feature. The cost curves are presented in terms of dollars versus exhaust gas volume. This relationship is based on a number of simplifying assumptions, which allow one to obtain quick, conceptual or study estimates with a minimum of effort. It must be borne in mind that these simplifications can lead to anomalous results at the extremes of the ranges, since the curves are presented in the form $y = ax^b$ and are based on regression analyses.

7.3.2 Particulate Control System Costs

On the basis of information in Reference 1 and the equipment cost curves in Figures 7-1 through 7-5, a number of cost curves have been developed that provide conceptual or study estimates of the capital and annualized costs of complete air pollution control systems. These curves provide costs for grass-roots installations. A retrofitted installation generally costs 10 to 30 percent more than a grass-roots installation and, depending on specific difficulties at a given site, the costs can be calculated on the basis of the latter percentage.

Annualized costs are based on 8700 h/y operation time. Since the annualized costs vary with operating time, the annualized costs for operations of less than 8700 h/y will be lower than those shown in Figures 7-6 through 7-14. For example, the annualized costs for 2000 h/y operation as a percent of the costs for 8700 h/y operation are approximately as follows:

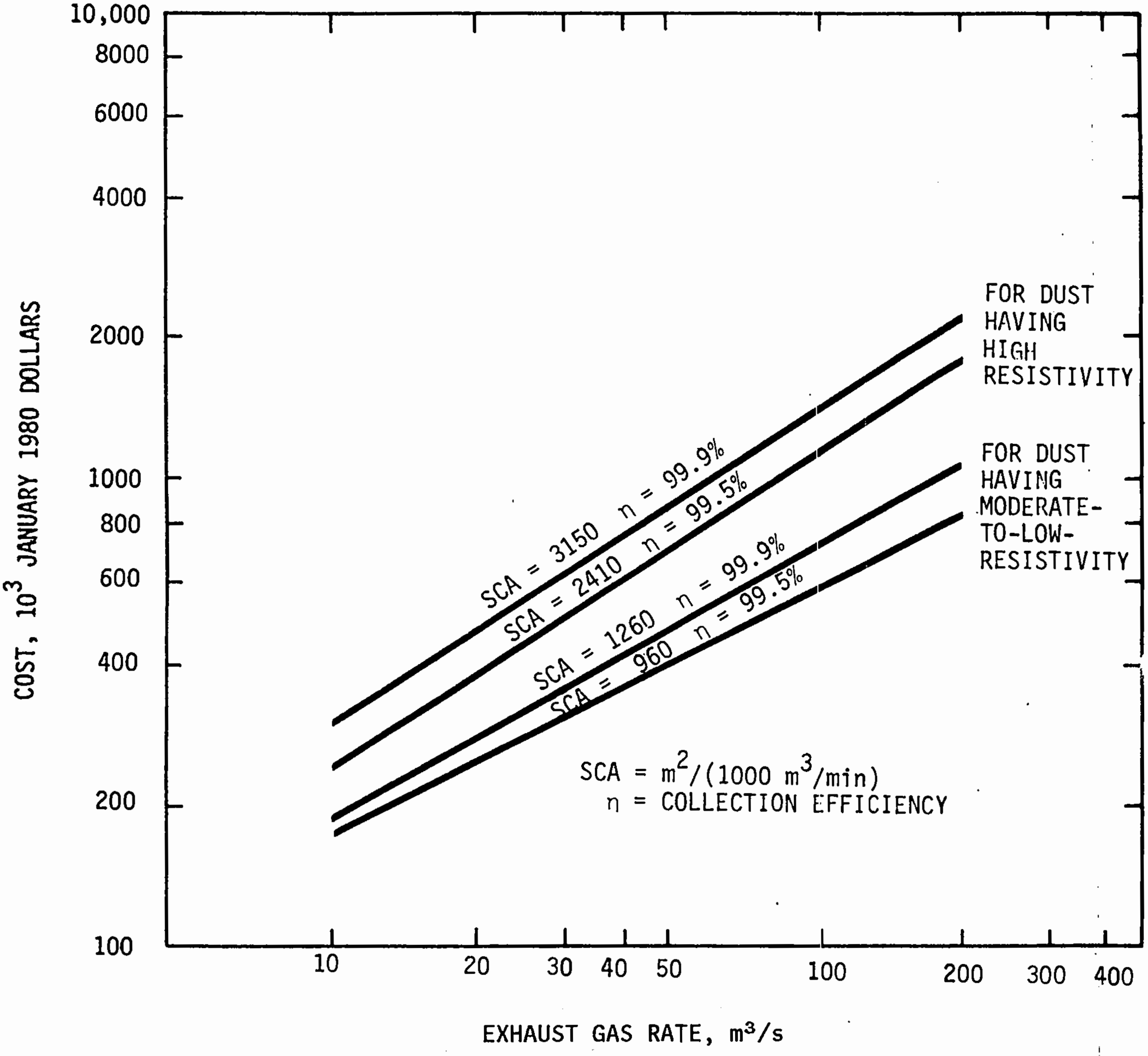


Figure 7-1. Cost of electrostatic precipitators; carbon steel construction, thermally insulated, FOB factory. (Instruments and controls and taxes not included.)

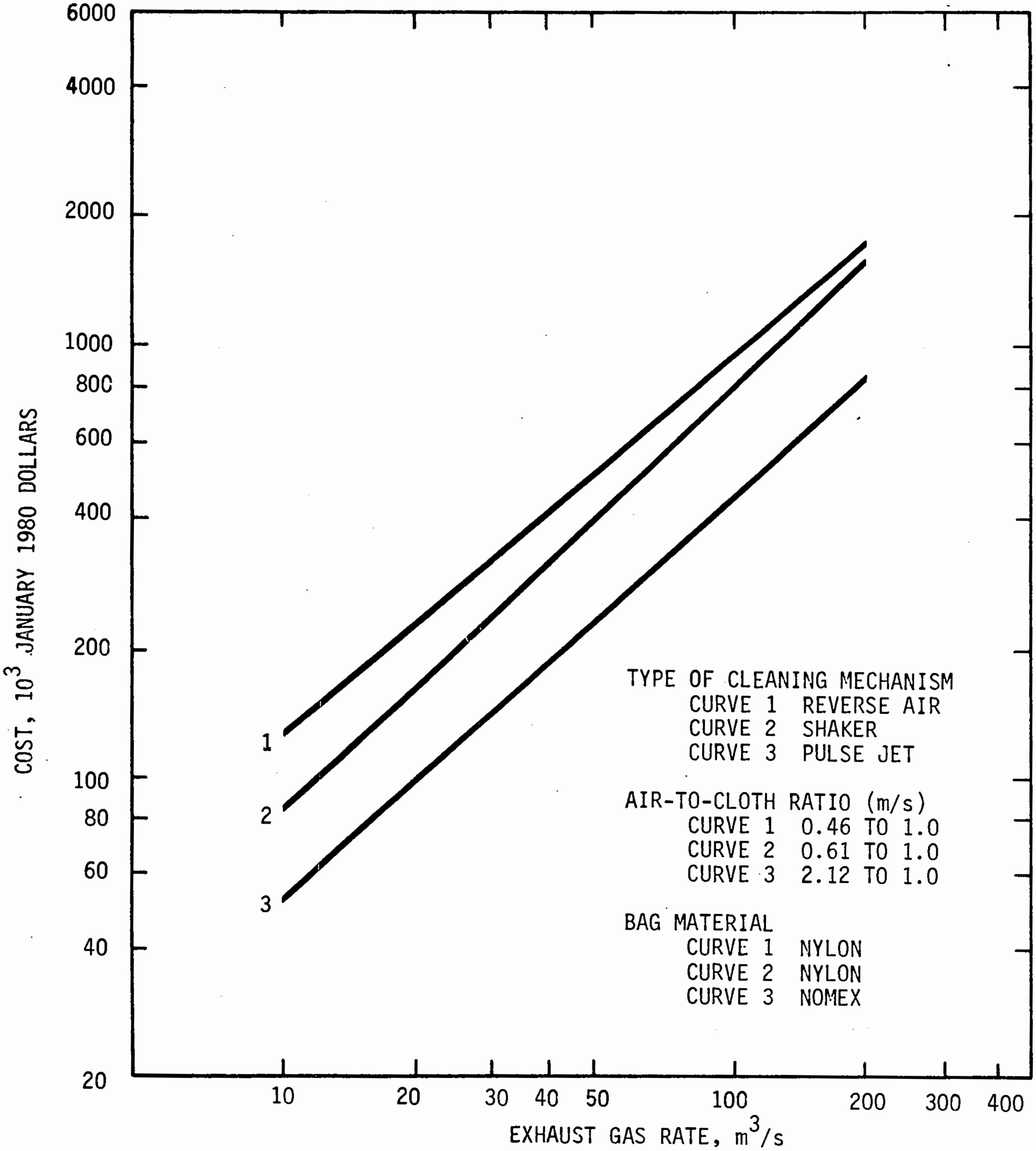


Figure 7-2. Cost of fabric filters, carbon steel construction, FOB factory. (Instruments and controls and taxes not included.)

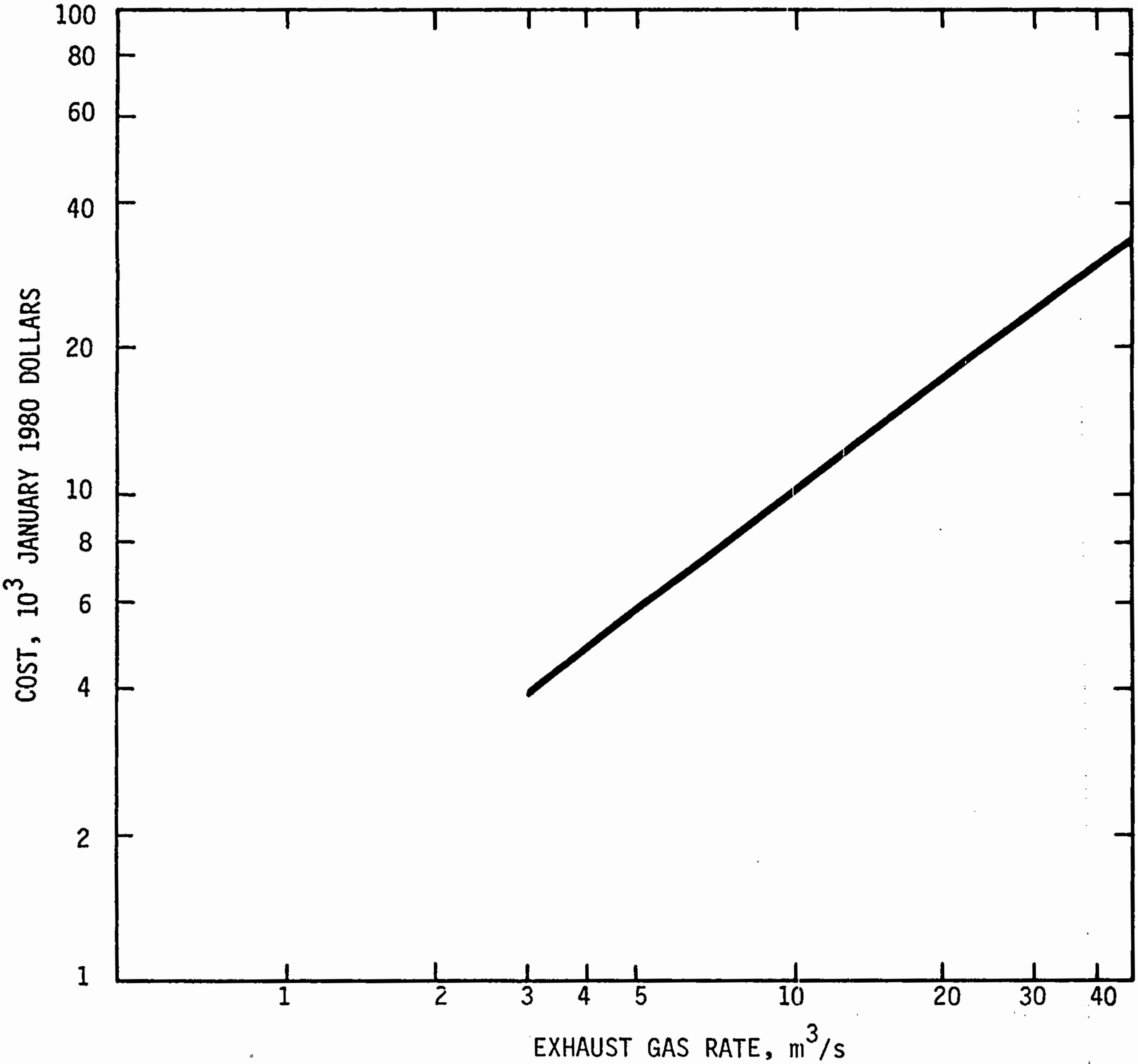


Figure 7-3. Cost of mechanical collectors, carbon steel construction, FOB factory. (Instruments and controls and taxes not included.)

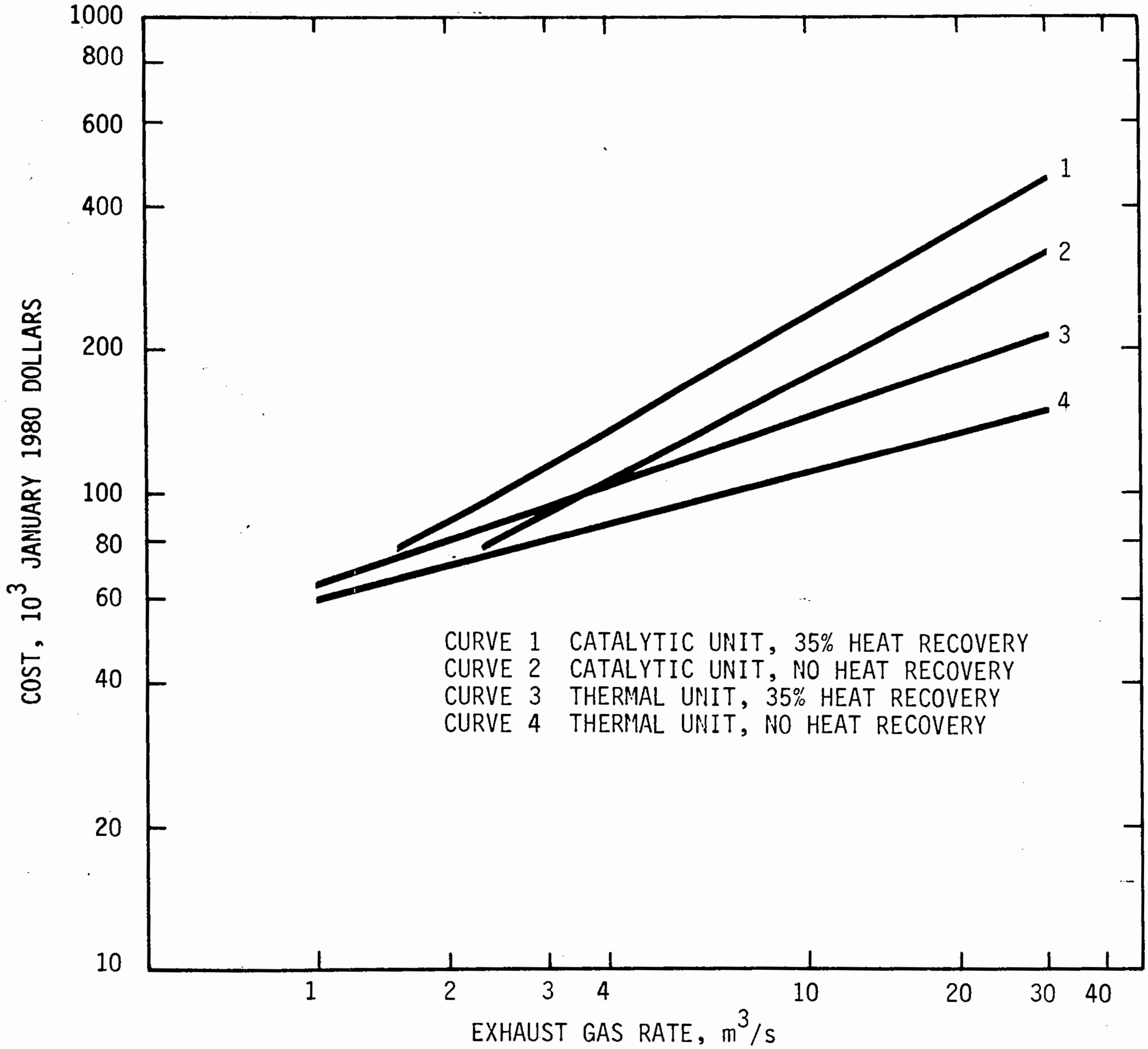


Figure 7-4. Cost of incinerators, FOB factory. (Instruments and controls and taxes not included.)

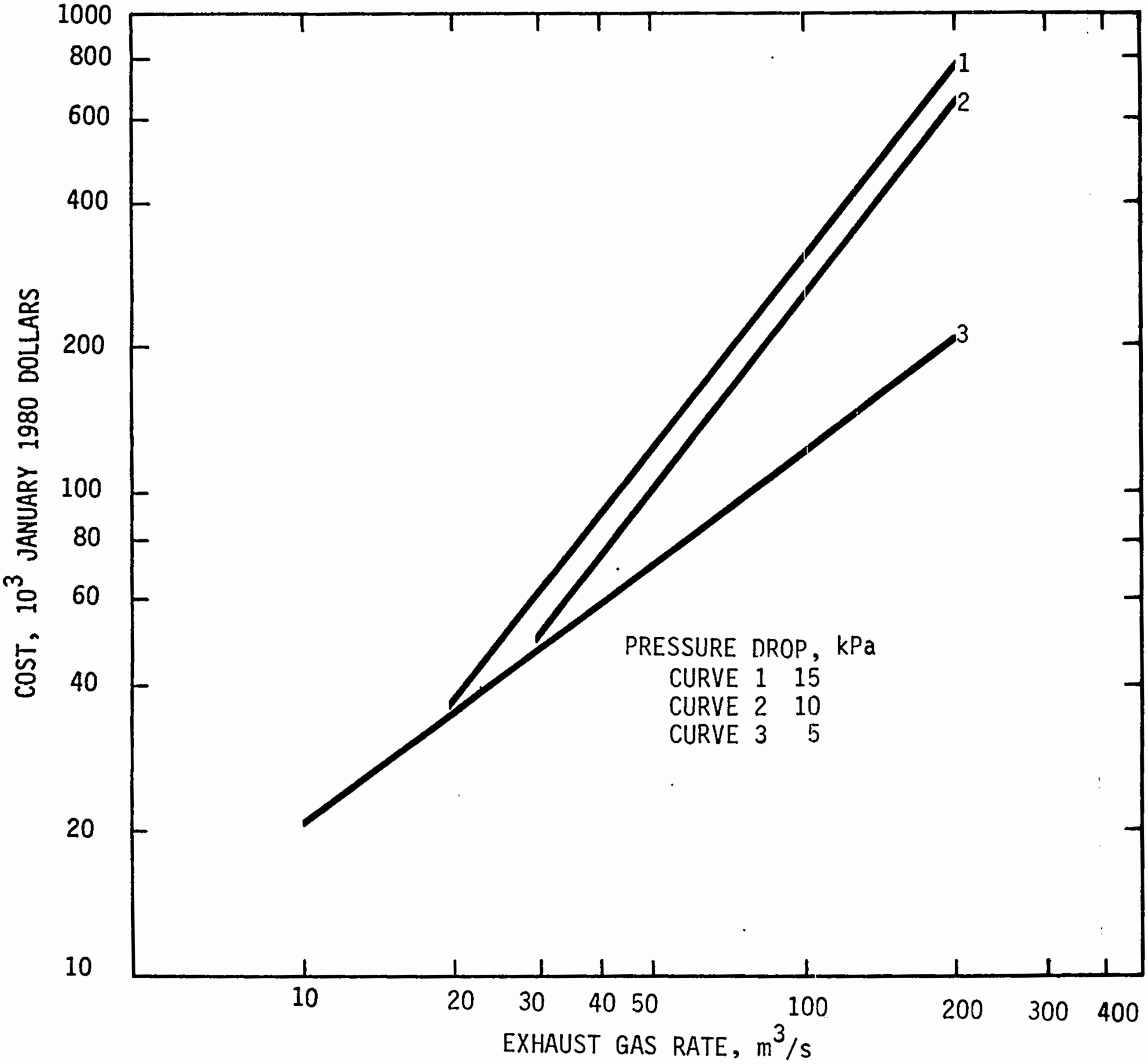


Figure 7-5. Cost of venturi scrubbers, unlined throat, carbon steel construction, FOB factory. (Instruments and controls and taxes not included.)

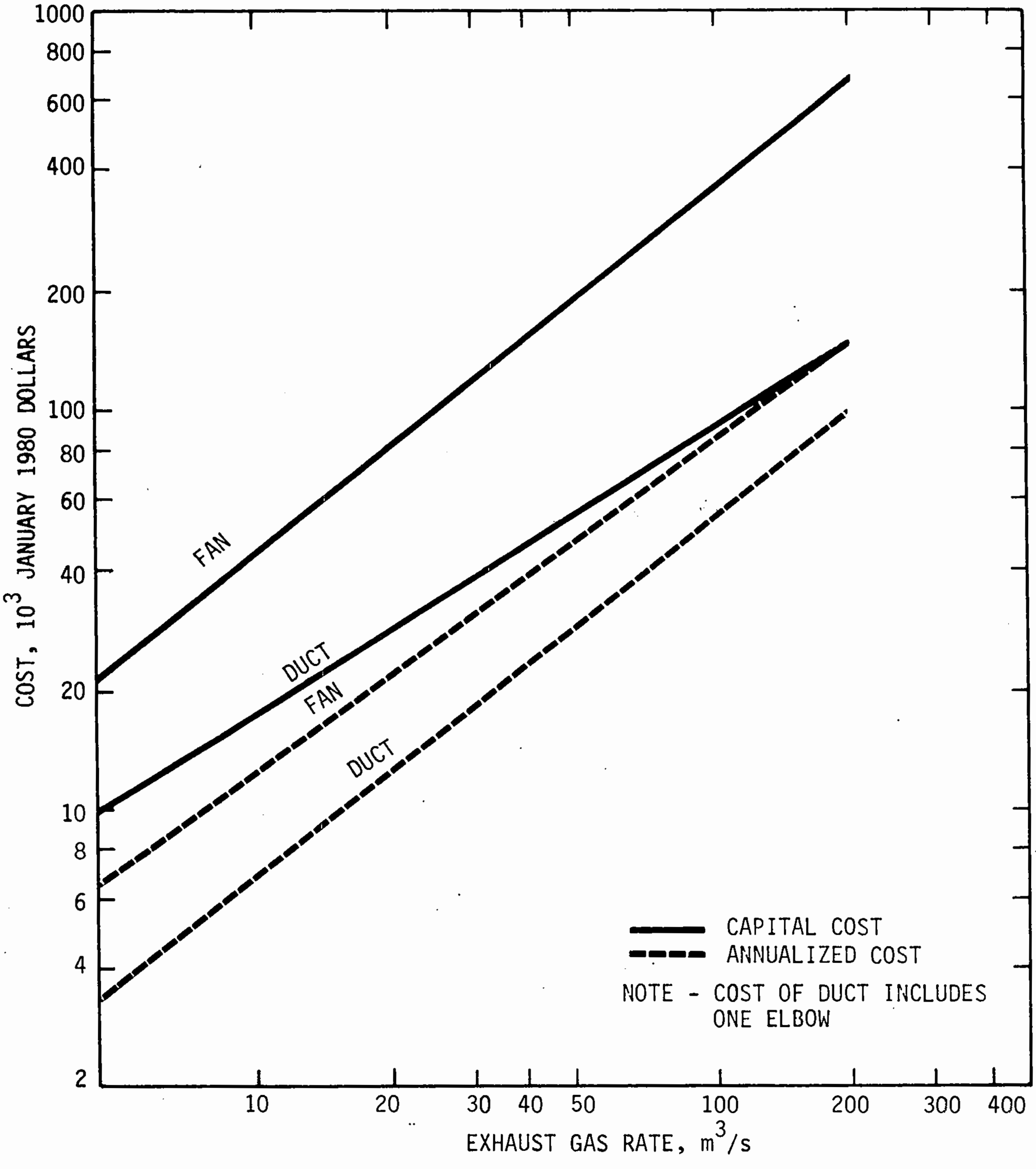


Figure 7-6. Capital and annualized costs of fans and 30.5 m length of duct.

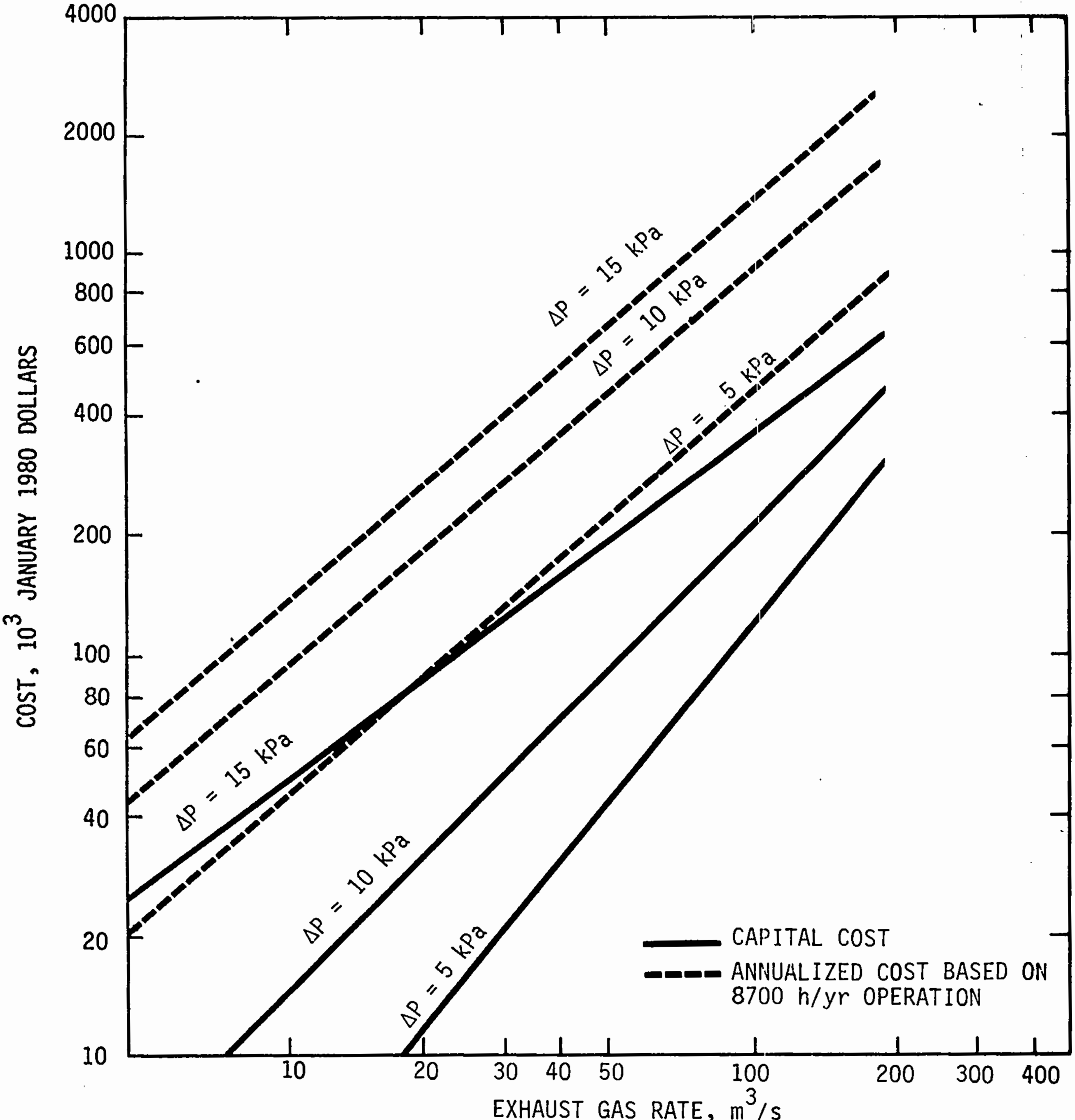


Figure 7-7. Capital and annualized costs of fan driver for various head pressures.

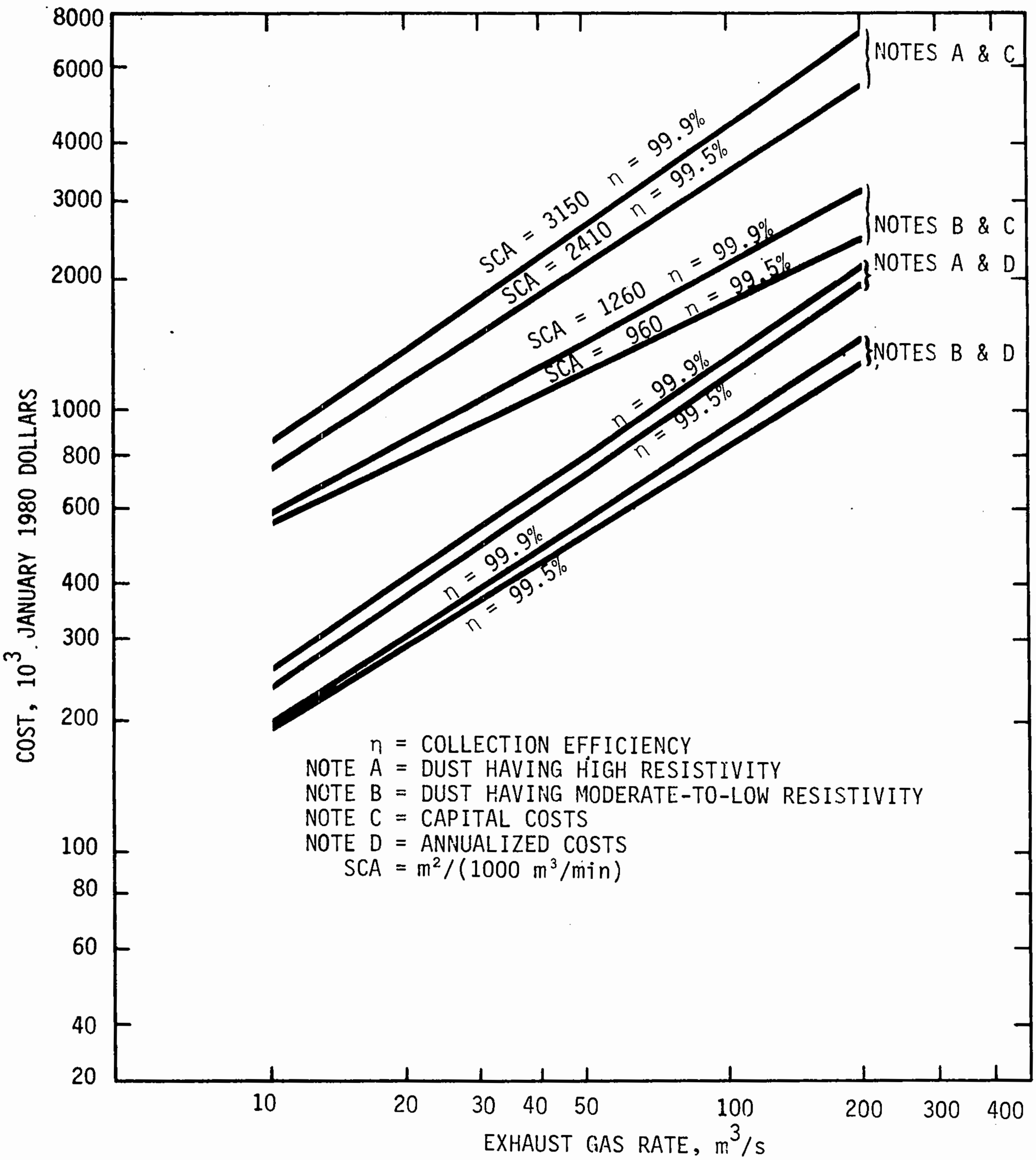


Figure 7-8. Capital and annualized costs of electrostatic precipitators, carbon steel construction.

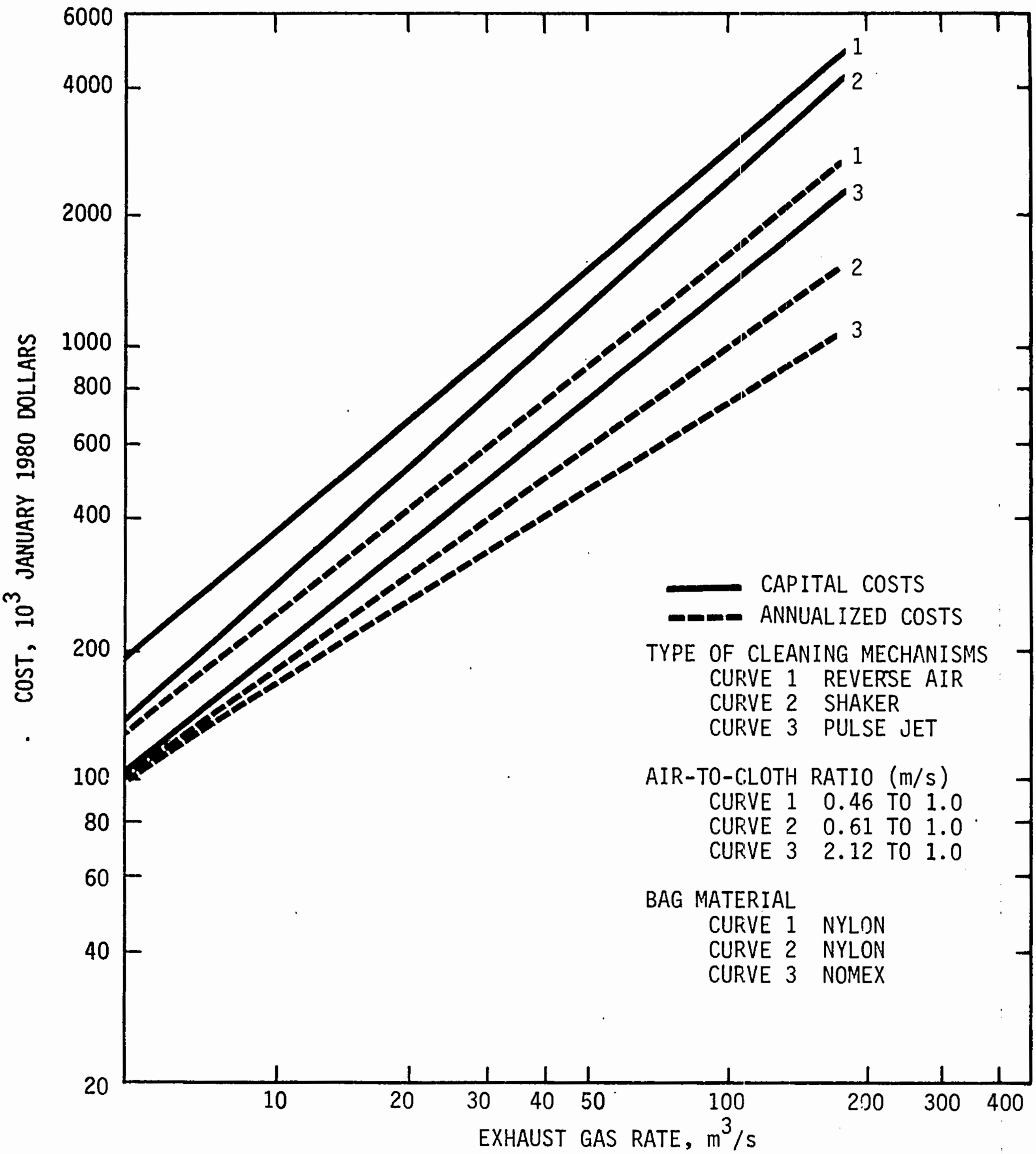


Figure 7-9. Capital and annualized costs of fabric filters, carbon steel construction.

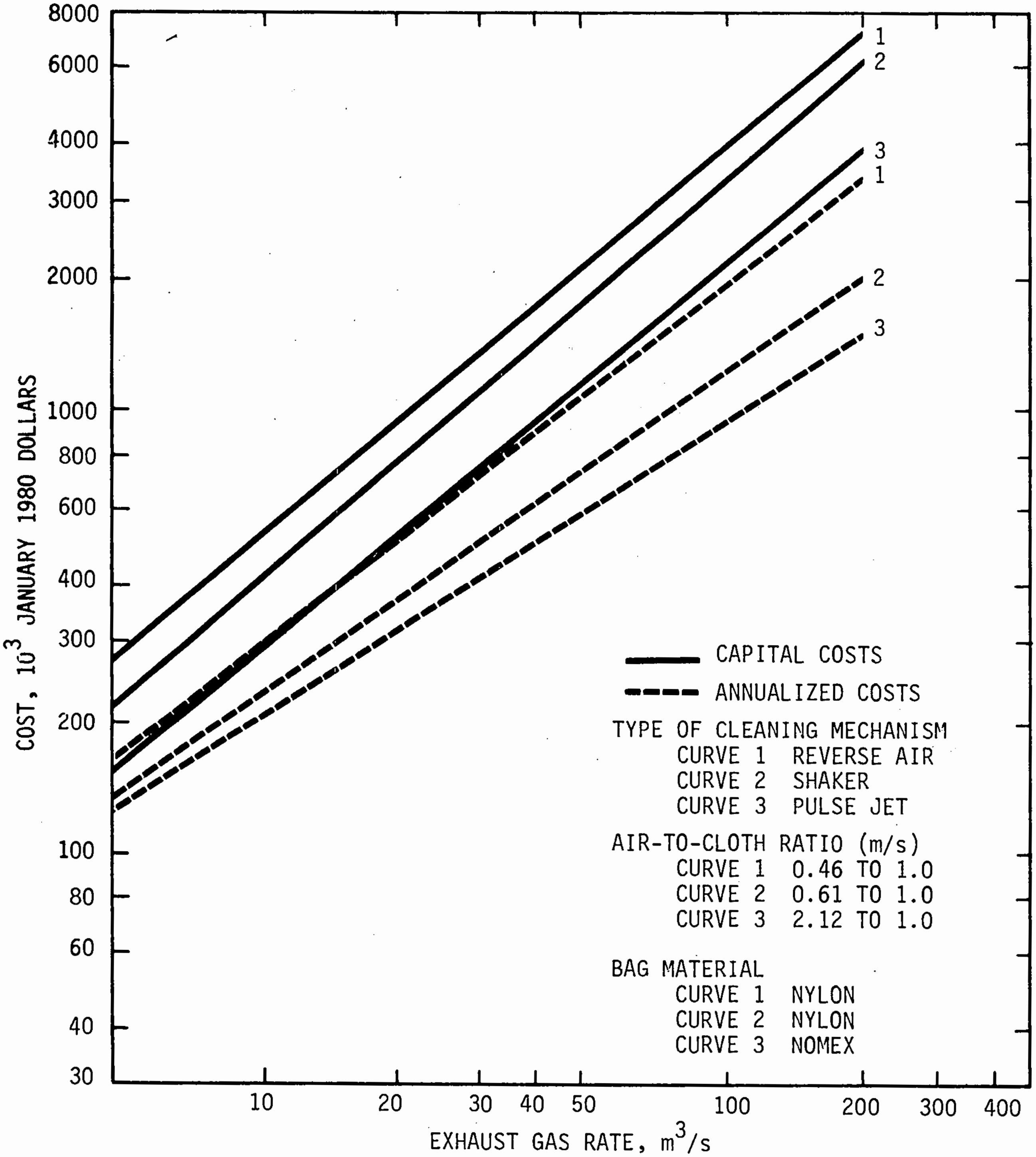


Figure 7-10. Capital and annualized costs of fabric filters, stainless steel construction.

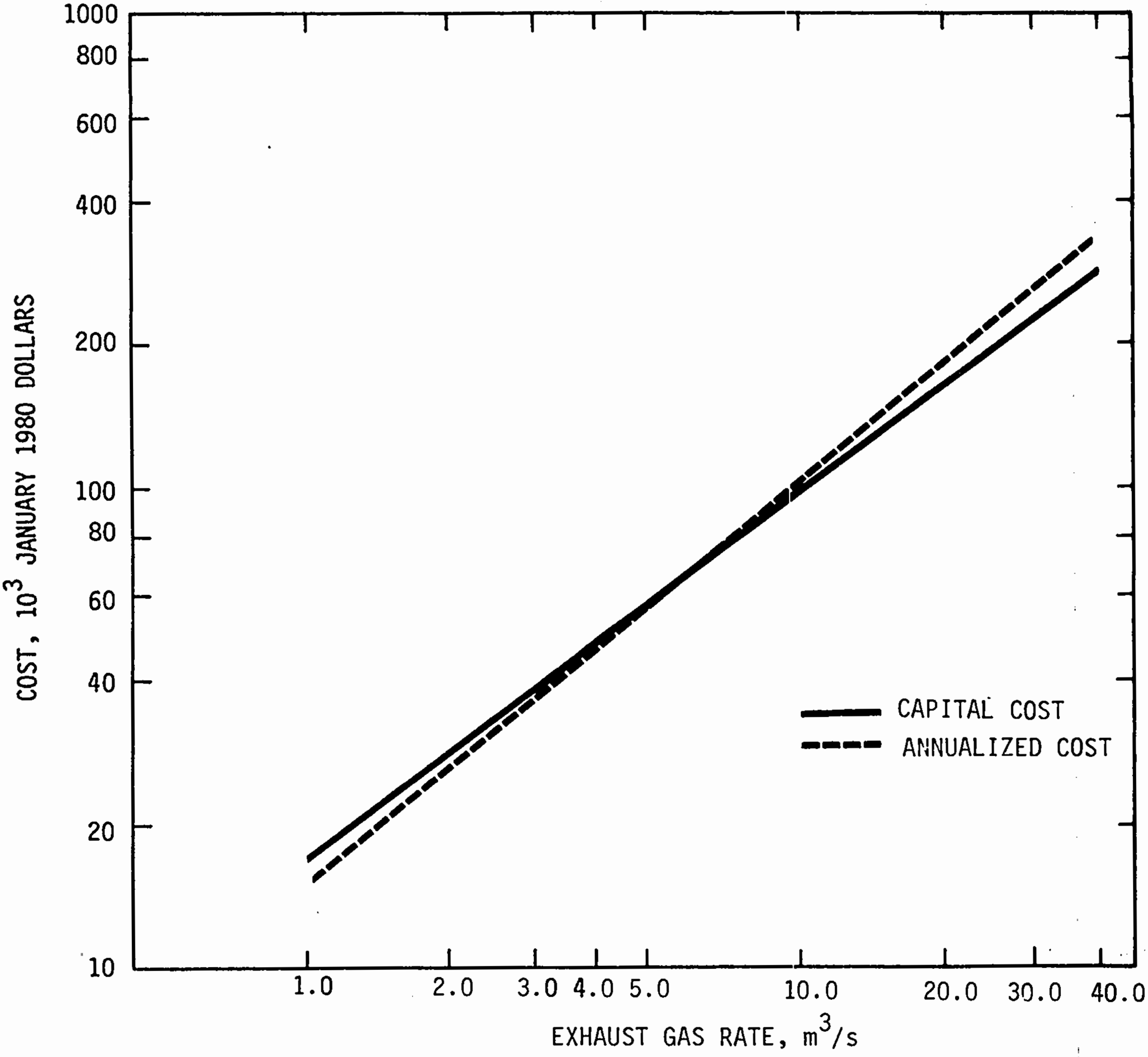


Figure 7-11. Capital and annualized costs of mechanical collectors, carbon steel construction.

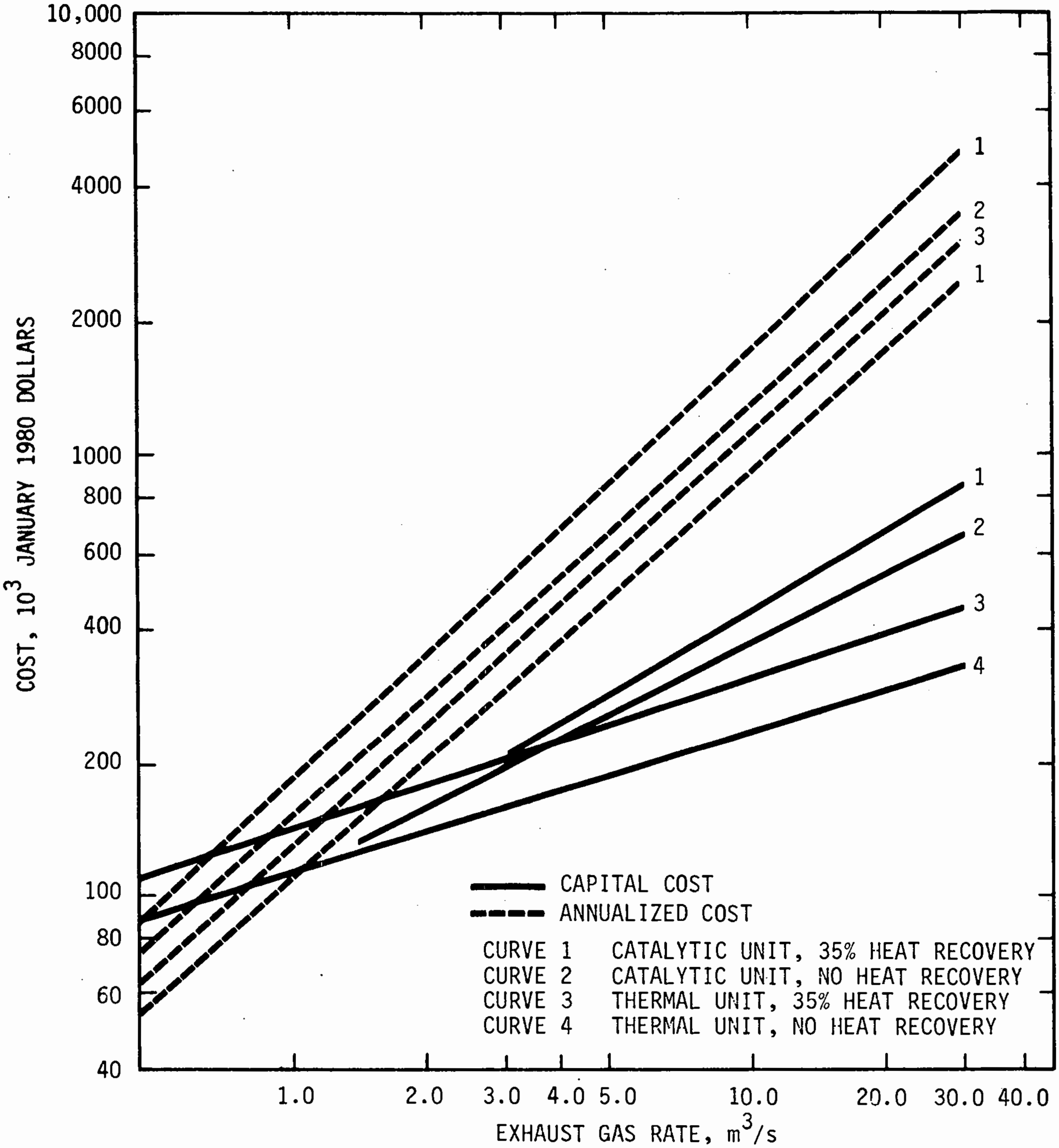


Figure 7-12. Capital and annualized costs of incinerators.

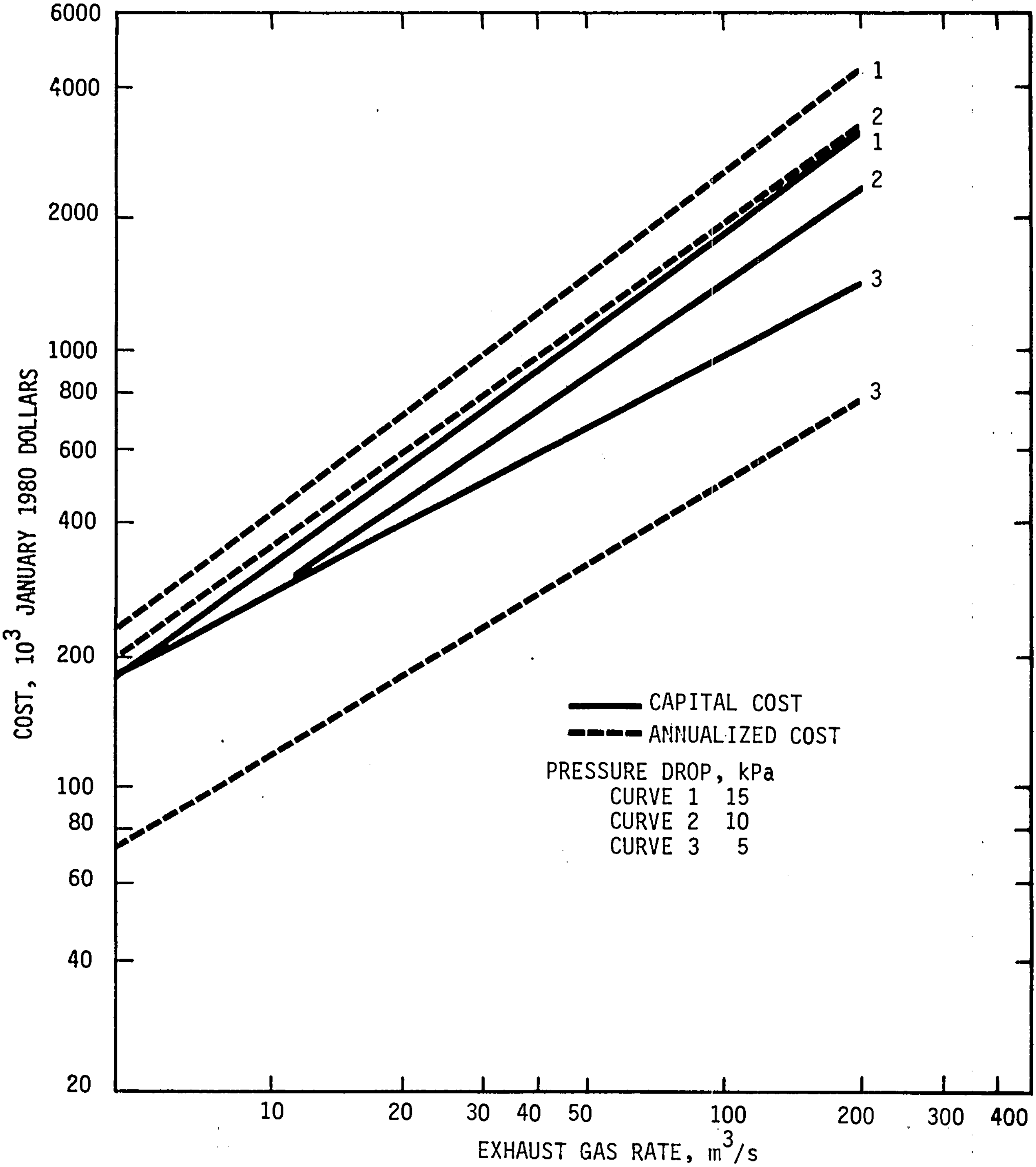


Figure 7-13. Capital and annualized costs of venturi scrubbers, carbon steel construction.

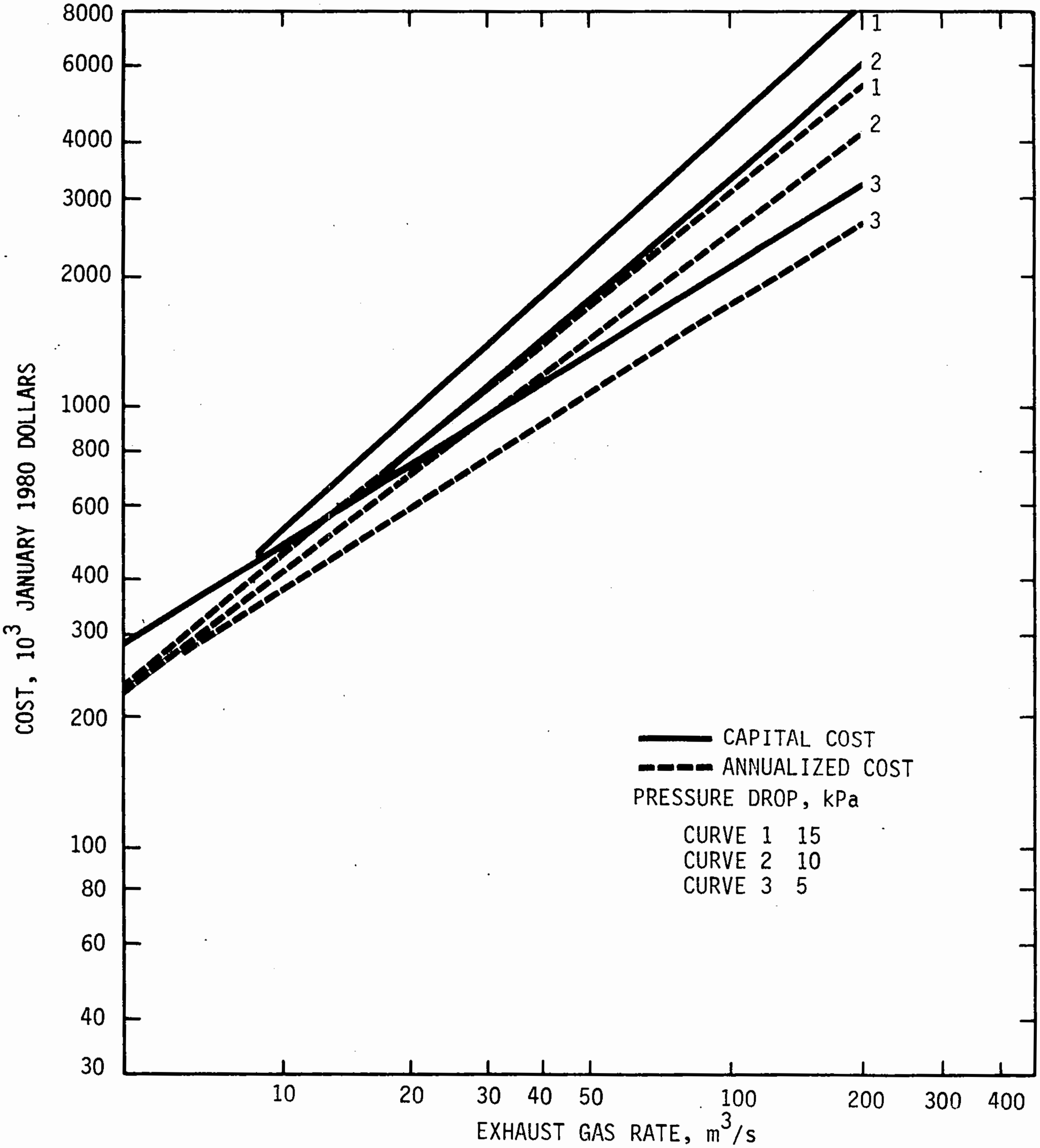


Figure 7-14. Capital and annualized costs of venturi scrubber, stainless steel construction.

Venturi scrubber	30 - 40 percent
Fabric filter	50 - 60 percent
Electrostatic precipitator	60 - 70 percent
Incinerator	25 - 35 percent

The annualized cost includes a disposal cost of $10 per ton, based on disposal of a nontoxic substance. It also includes a capital charge based on an assumed equipment life of 15 years and an opportunity cost of 15 percent.

Each of the control system cost curves includes the costs of auxiliary equipment normally associated with such a system. In some instances one may wish to know what the system would cost either with or without the ductwork, fan, and fan drive. The capital and annualized costs of the components are shown in Figures 7-6 and 7-7.

7.3.2.1 Electrostatic Precipitator. Figure 7-8 presents cost curves for systems utilizing an electrostatic precipitator housed in an insulated, carbon steel shell. The assumption is made that the uncontrolled gas stream is normally vented to a stack. Thus, the necessary fan and ductwork are considered part of the process. Costs are presented for three levels of control efficiency based on medium- and high-reactivity dust. For a given collection efficiency, high-resistivity dust requires a greater SCA (specific collection area) and the cost of the ESP is thus increased. For purposes of estimating equipment costs, plate area was calculated according to the Deutsch equation with particle drift velocities of 0.036 m/s for high-resistivity dusts and 0.086 m/s for low-resistivity dusts. Dusts such as fly ash from low-sulfur coal combustion and cement kiln dust have high resistivity.

7.3.2.2 Fabric Filters. Fabric filters are commonly used across a broad range of exhaust gas volumes. Low-temperature and low-volume exhaust streams from conveyor transfer points are normally vented to a fabric filter. On the other hand, high-temperature and high-volume exhausts from electric arc furnaces are also often vented to a fabric filter. Figures 7-9 and 7-10 present cost curves for a variety of fabric filter applications. Costs are presented for filters utilizing each type of bag-cleaning mechanism. The cost curves assume that the fan and drive are process equipment. The control costs include tie-in ductwork, a dust handling conveyor, and a dust storage bin. The costs of thermal insulation and heaters (necessary to prevent condensation in some applications) are not reflected in the cost curves. Separate curves are presented for stainless steel construction.

7.3.2.3 Mechanical Collectors. Capital and annualized cost curves for mechanical collector systems are shown in Figure 7-11. System costs include hooding to capture the exhaust at the emission point, ducting, a fan and drive, and a dust storage bin. The system cost is based on carbon steel construction. Collection efficiency for this type of system generally ranges from 80 to 90 percent, depending on the particle size distribution and inlet grain loading.

7.3.2.4 Incinerators. Incinerators are of two basic types, thermal[a] and catalytic. Although thermal incinerators are less costly from a capital cost standpoint, the fuel savings associated with catalytic units make them attractive for compatible exhaust streams. Both types of units may recover heat and thereby reduce the fuel requirements. The additional cost of the heat exchangers must be compared with the fuel savings on a case-by-case basis. Additionally, the use of catalytic incinerators for control of particulate matter is limited to substances that will not blind or poison the catalytic mesh. Figure 7-12 presents cost curves for both types of units, based on an exhaust stream at 25 percent of the lower explosive limit (LEL). The costs of units having a heat exchanger are based on a 35 percent heat recovery rate. Exhaust streams that are amenable to incineration are normally exhausted to the atmosphere. Thus for purposes of the cost curves presented herein, the fan and drive are considered process equipment. The cost curves include the cost of ductwork to tie the incinerator into the process vent system.

7.3.2.5 Venturi Scrubbers. Venturi scrubber use ranges from control of small process fugitive exhaust streams to control of high-volume point

[a] Note: Direct-fired incinerators considered as thermal incinerators for purposes of this analysis.

sources such as basic oxygen furnaces. Figures 7-13 and 7-14 present cost curves for a variety of pressure drops. The costs include a clarifier and circulating pump for the scrubber liquor, a fan and drive, and ductwork sufficient to tie the scrubber into the process exhaust stream.

7.4 COST OF FUGITIVE EMISSION CONTROL

There is no single method of estimating costs of control of fugitive particulate emissions. Because of the great variety of sources and control methods, cost estimation must be specific to the method of control.

Many industrial process fugitive emissions (IPFE) are controlled with the same types of equipment used for controlling process emissions. The three main approaches to control of IPFE are ventilation, wet suppression, and optimization of operations. Ventilation makes use of hooding, ductwork, enclosures, and control devices such as baghouses or ESP's. Use of similar types of equipment, with the possible addition of some auxiliaries, permits use of capital cost estimating techniques previously described and the cost curves presented in Section 7.3. The annualized costs for most ventilation control techniques may also be estimated from the curves in this section.

The costs of controlling IPFE with wet suppression techniques are not amenable to the estimating procedures described in Section 7.2 because these control techniques, applied to materials-handling operations such as conveyors and unloading stations, do not make use of the same types of equipment used in controlling process emissions. Their cost depends on the amount of material handled and the efficiency required.

Table 7-4 presents reported cost data for spray and charged fog systems applied to rail car unloading and conveyor transfer stations. The foam-type spray system at a single transfer point would have a total capital cost of about $18,000; implementing such a system handling 2.0 Gg of material per year at an integrated iron and steel plant has been estimated to cost $240,000.[2] Initial cost of the charged fog-type system at a single transfer point would be about $15,000.[3]

Because most of the other techniques used in controlling fugitive particulate emissions do not require large capital expenditures, annual direct operating costs are presented in place of annualized costs. Indirect annual costs are not considered.

TABLE 7-4. TYPICAL COSTS OF WET SUPPRESSION OF INDUSTRIAL PROCESS FUGITIVE PARTICULATE EMISSIONS

	Estimated control efficiency, %	Initial cost, January 1980 dollars	Unit operating cost, January 1980 dollars
Railcar unloading station (foam spray)[a]	80	37,000	NR
Railcar unloading station (charged fog)[b]	NR	128,000[c]	NR
Conveyor transfer point (foam spray)[a]	70-95	18,000	0.022 to 0.055/Mg material treated
Conveyor transfer point (charged fog)[b]	NR	15,000[d]	NR

NR = Not reported.

[a] Reference 2.

[b] Reference 3.

[c] Based on use of 16 large devices at $8,000 each.

[d] Based on use of 3 small devices at $5,000 each.

The cost of controlling fugitive dust emissions is generally dependent upon the method of application, suppressant or stabilizer used, and desired control efficiency. Wet suppression and stabilization are the two most common approaches to dust control.

Table 7-5 presents capital and operating costs for wet suppression of fugitive dust from an unpaved road, a storage pile, and a disturbed or unvegetated outdoor (exposed) area. The costs for the unpaved road are based upon the use of a 11.35-m^3-capacity, nonpressurized spray truck operating twice daily. The control costs for the storage pile are based upon the use of a stationary, elevated water spray system including sprayers, piping, pumping, wind instruments, and installation costs. Operating costs are not presented. For the exposed area, costs are based on the following assumptions: the equipment includes piping and sprinklers, the unit is moved by hand, and the application rate is 0.473 m^3 of water per minute with an effective spray radius of 33.5 meters.[2]

Table 7-6 presents cost data for application of stabilization techniques to various fugitive dust sources. The three sources are again an unpaved road, a storage pile, and an exposed area. Methods of stabilization are oiling, chemical and vegetative stabilization, paving, and use of aggregate or chips.[2]

Operating costs for oiling and chemical stabilization of the unpaved road surface are based on use of a 11.35-m^3-capacity, nonpressurized spray truck for application. The capital costs for chemical stabilization of a storage pile are assumed to be the same as for wet suppression.[2] The costs of vegetative stabilization of exposed areas are highly variable as a result of the wide range of climate and the physical and chemical properties of the soil. Where topsoil is required, the costs may be higher than those shown in Table 7-6.

Other techniques available for control of fugitive dust include street sweeping, vacuuming, and flushing. Table 7-7 presents costs for these control techniques. The lower capital cost figure for sweeping is based on the use of a trailer-type sweeper; the higher capital cost figure is based on use of a self-propelled unit with a spray bar. The initial cost figure for flushing applies to a 1.135-m^3 street flusher, excluding truck chassis. Water requirements are significant.[5]

TABLE 7-5. COST ESTIMATES FOR WET SUPPRESSION OF FUGITIVE DUST[2]

Source method	Estimated control efficiency, %	Initial capital cost, January 1980 dollars	Annual operating cost, January 1980 dollars
Unpaved road-regular watering	50	13,000/truck	25,000/truck
Storage pile-regular watering	80	14,000/system	NR
Exposed area-watering	50	2,000/hectare	10-27 hectare

NR = Not reported.

TABLE 7-6. COST ESTIMATES FOR STABILIZATION OF FUGITIVE DUST

Source method	Estimated control efficiency, %	Initial capital cost, January 1980 dollars	Annual operating cost, January 1980 dollars
Unpaved road-oiling[a]	75	1860/km	22,360/km[b]
Unpaved road-chemicals (lignin or coherex)[a]	90-95	3700-9300/km	3700-9300/km
Unpaved road-asphaltic paving[a]	90	21,100-37,900/km	3100-5600/km
Unpaved road-oil (double chip surface)[a]	80	6700/km	1240-3100/km[d]
Exposed areas-oiling[a]	80	250/hectare	NR
Exposed areas-chemicals[a]	70	2000/hectare	75-150/hectare
Exposed areas-paving, asphalt[a]	95	29,500/hectare	NR
Storage piles-surface crusting chemicals[a]	99	14,000/system	0.05-0.10/m^2
Exposed areas-vegetation[e]	25-100	370-1480/hectare	NR[f]

NR = Not reported.
[a] Reference 2.
[b] Based on monthly application.
[c] Based on resurfacing every five years and 15% opportunity costs.
[d] Based on reapplication every 2-3 years and 15% opportunity costs.
[e] Reference 4.
[f] Dependent on type of vegetation planted, condition of soil, and climate.

TABLE 7-7. COST ESTIMATES FOR SWEEPING AND FLUSHING OF FUGITIVE DUST SOURCES[2]

Source method	Estimated control efficiency, %	Initial capital cost, January 1980 dollars	Annual operating cost, January 1980 dollars[a]
Paved road-sweeping	70	5,000-15,000/ truck	21,000/truck
Paved road-vacuuming	75	28,000/truck	26,000/truck
Paved road-flushing	80	14,000/truck	21,000/truck

[a] Cost per kilometer depends on nature of process and the site.

REFERENCES

1. Neveril, R. B. Capital and Operating Costs of Selected Air Pollution Control Systems. EPA-450/5-80-002, December 1978.

2. Bohn, R., T. Cuscino, Jr., and C. Cowherd, Jr. Fugitive Emissions from Integrated Iron and Steel Plants. EPA-600/2-78-050. March 1978.

3. Daugherty, D. P. and D. W. Coy. Assessment of the Use of Fugitive Emission Control Devices. EPA-600/7-79-045. February 1979.

4. Richard, G., and D. Safriet. Guideline for Development of Control Strategies in Areas with Fugitive Dust Problems. EPA-450/2-77-029. October 1977.

5. PEDCo Environmental, Inc. Technical Guidance for Control of Industrial Process Fugitive Particulate Emissions. EPA-450/3-77-010. March 1977.

SECTION 8

EMERGING TECHNOLOGIES

With the growing awareness of the environmental and health impacts of particulate emissions, there has been a need for more effective control technology. The emergence of new energy production methods also dictates that particulate control devices operate under more stringent conditions of temperature, pressure, and flue gas properties. For these reasons there is an increasing demand for advanced particulate removal systems to supplement or replace the conventional control techniques.

The advanced particulate control systems have been developed only recently. Most emerging techniques are essentially hybrids of technological elements associated with first-generation systems. This section examines some of the novel concepts being developed for control of particulate emissions. Discussion of each concept is followed by a proposed overall design, together with data that indicate system performance.

8.1 ADVANCED SCRUBBING TECHNIQUES

The prevailing limitation of conventional scrubbing technology is the high energy usage required to capture submicron particulate and the associated high operating costs. The limitations are principally due to the inefficient use of available energy and the laws governing particle behavior. In use of conventional scrubbing to capture the entrained particles (which generally comprise less than 1 percent of the stream's mass), energy is applied to the complete mass of the stream (gas molecules and particles). Furthermore, exponentially increasing energy consumption is required in conventional scrubbing to capture progressively smaller submicrometer-size material. The combination of these two factors can render conventional particulate scrubbing noncompetitive with other conventional removal techniques.

Many industrial processes emit gaseous and particulate-laden streams containing corrosive, sticky materials. For these processes conventional nonscrubbing techniques (i.e., baghouses, electrostatic precipitators, and mechanical collectors) are not applicable for control purposes. Consequently, environmental concerns with increasing energy costs combine to encourage development of new scrubbing techniques.

The following subsections describe the technical and performance characteristics of several emerging scrubbing techniques. Scrubbing systems that are electrostatically and hydrodynamically enhanced are shown to be more energy-efficient and effective in capture of submicrometer-size material than their conventional counterparts.

8.1.1 Air Pollution Systems, Inc. Electrostatic Scrubber (ES)

The ES system is basically an electrostatic charger followed by a conventional venturi scrubber (Figure 8-1).[1] The system incorporates a patented high-intensity ionizer, which electrostatically charges the particles in the gas stream before they enter a conventional low-energy scrubber. The ionizer, designed with a unique electrode configuration, produces a high electric field strength (10 to 15 kV/cm) with high ion densities. These levels of field strength and ion density, higher than those of the conventional ESP, effectively charge both submicrometer- and supermicrometer-sized particles. The attractive force between the charged particles and droplet is additive to the inertial and other forces acting in the venturi scrubber. These electrostatic forces account for the enhanced collection of the complete size range of available particles in the gas stream. Figure 8-2 illustrates the higher removal efficiency of fine particulate with the electrostatic scrubber relative to the efficiency of a venturi scrubber.[1]

A field pilot test program with the UC electrostatic scrubber was conducted on a urea prilling tower. The emission stream contained 85 percent submicron material at a concentration of 91.5 mg/m^3. At a pressure drop of 19.0 cm W.C. (7.5 in. W.C.), performance measurements by plant personnel indicated an average overall efficiency of 93.5 percent and zero opacity.

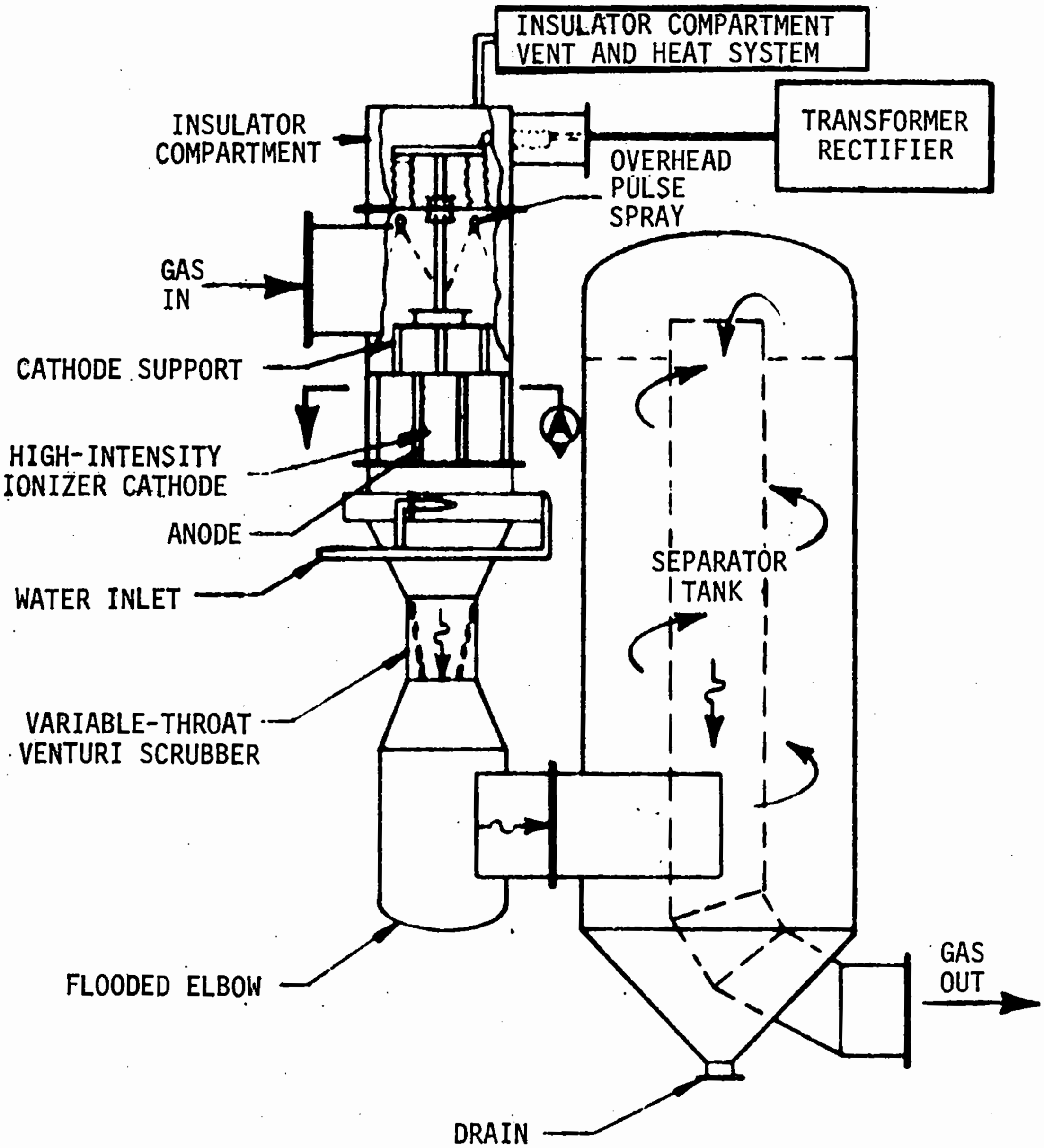


Figure 8-1. APS electrostatic scrubber.[1]

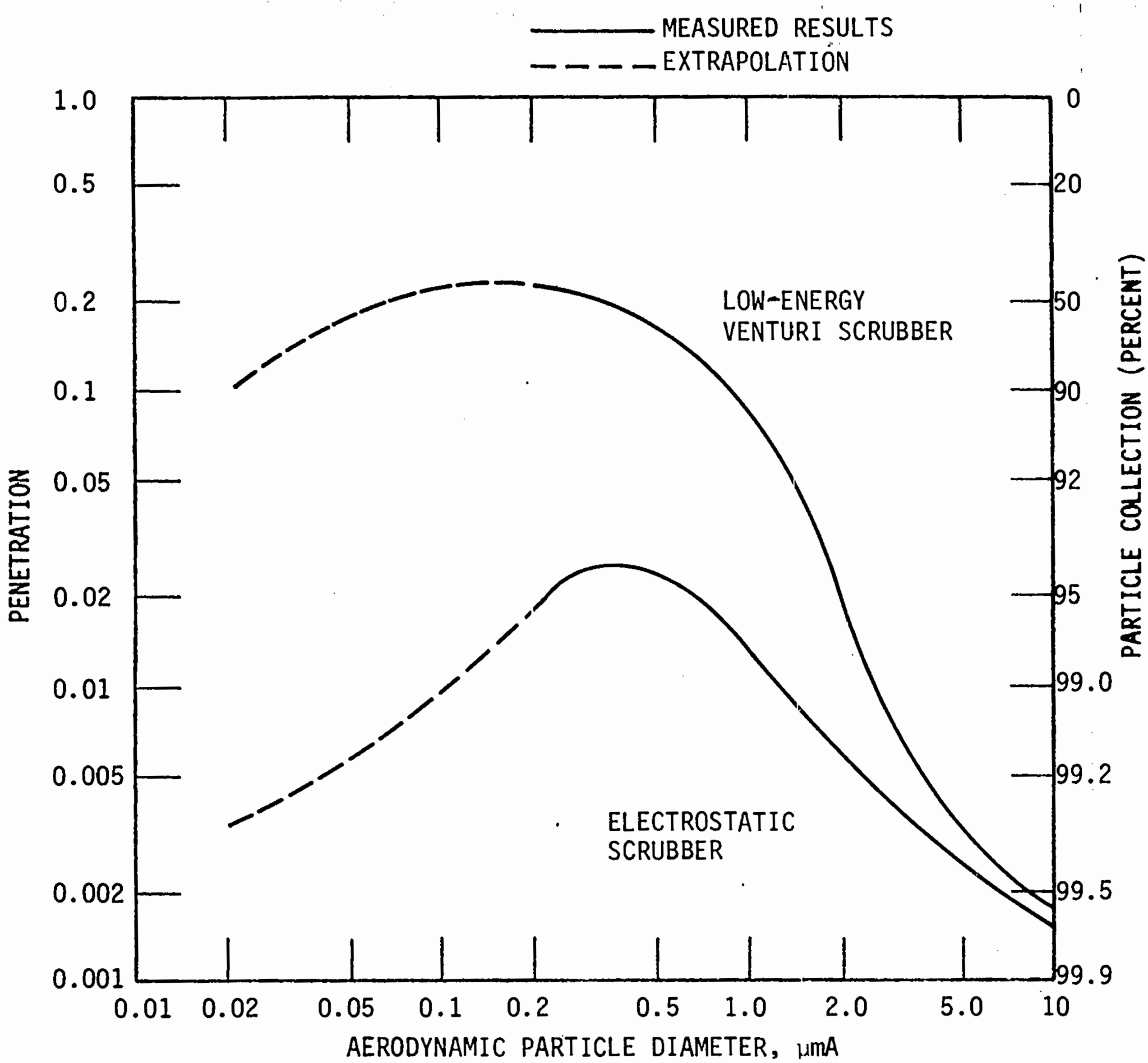


Figure 8-2. Fraction efficiency performance of APS electrostatic scrubber.[1]

Estimates of electrical operating power based on laboratory and pilot test results, indicate 0.24 kW per m^3/s to convert a low-energy venturi scrubber into the equivalent of a high-energy scrubber with a UC ionizer module.[1]

8.1.2 TRW Charged Droplet Scrubber (CDS)

The CDS system passes water through small-diameter tubes, and electrostatically atomizes and charges the water droplets.[2] The droplets range in diameter from 60 to 250 μmA and have a high surface charge density. The charged droplets are immediately exposed to and interact with slow-moving (∿2 m/s) dust-laden gas streams (Figure 8-3). The electric field in the droplet-particle mixing region accelerates the charged droplets to high velocities (∿30 m/s). These conditions of relatively slow-moving particles and fast-moving charged droplets account for high collision rates due to enhanced inertial and electrostatic collection mechanisms.

Successful results of laboratory and pilot field tests with the CDS system were followed by installation of a 51,000 m^3/h demonstration unit on a coke oven battery.[3] Emissions consisted of fluctuating concentrations (114 to 755 mg/m^3) of submicron sticky hydrocarbons and micron-sized high-conductivity carbon black. Overall removal efficiencies ranged from 91.0 percent to 94.3 percent, and fractional efficiencies ranged from 80 percent to 99 percent (Figure 8-4) for various inlet loading and CDS operating conditions. The CDS design summary is shown in Table 8-1.

Low total energy and water consumption, 1.41 to 2.0 W per m^3/s and 0.11 to 0.13 liter/m^3, respectively, were demonstrated over most of the test conditions. Capital and annualized costs are not available in the literature, but several CDS systems have been purchased and installed on industrial and municipal incinerators, and in the iron and steel and the pulp and paper industries in Japan.

8.1.3 University of Washington Electrostatic Droplet Scrubber (UWEDS)

The UWEDS system involves the use of electrostatically charged water droplets to capture suspended particles electrostatically charged to the opposite polarity of the droplets. The particles are negatively charged in the corona section and flow into a scrubber chamber, into which positively charged water droplets are sprayed. The scrubbed gas stream with entrained

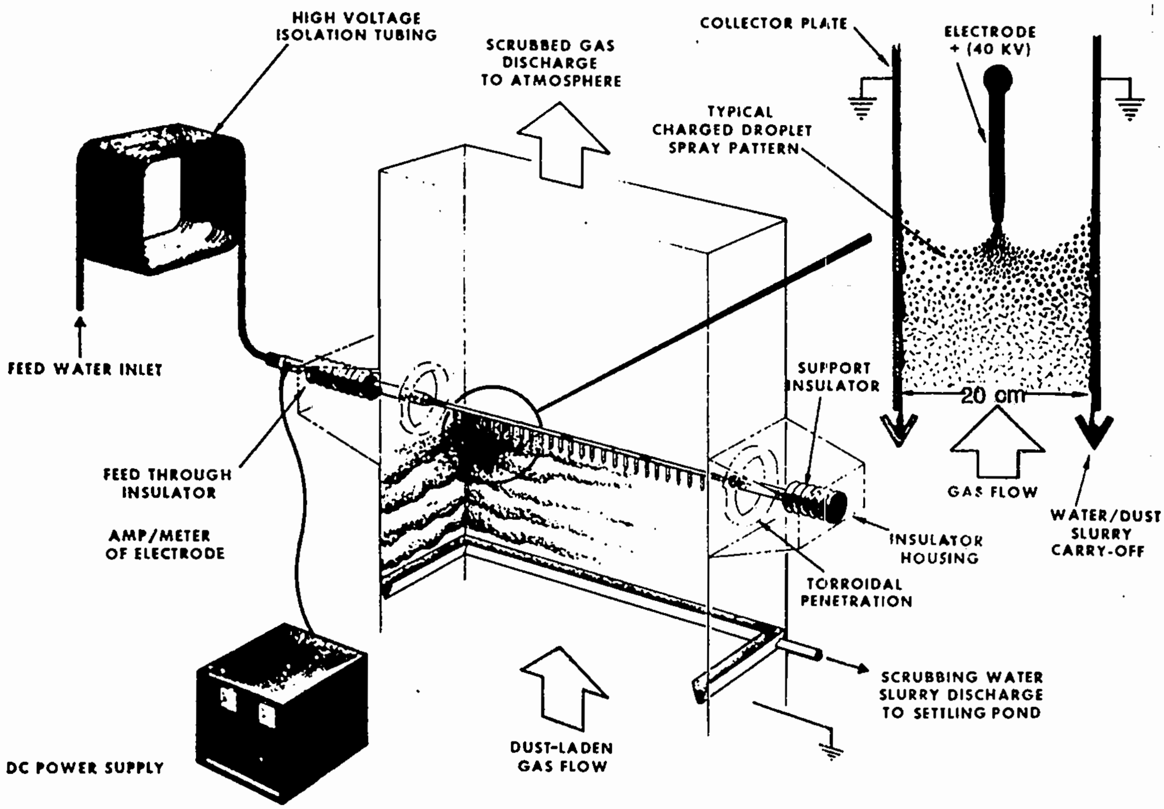


Figure 8-3. TRW charged droplet scrubber.[2]

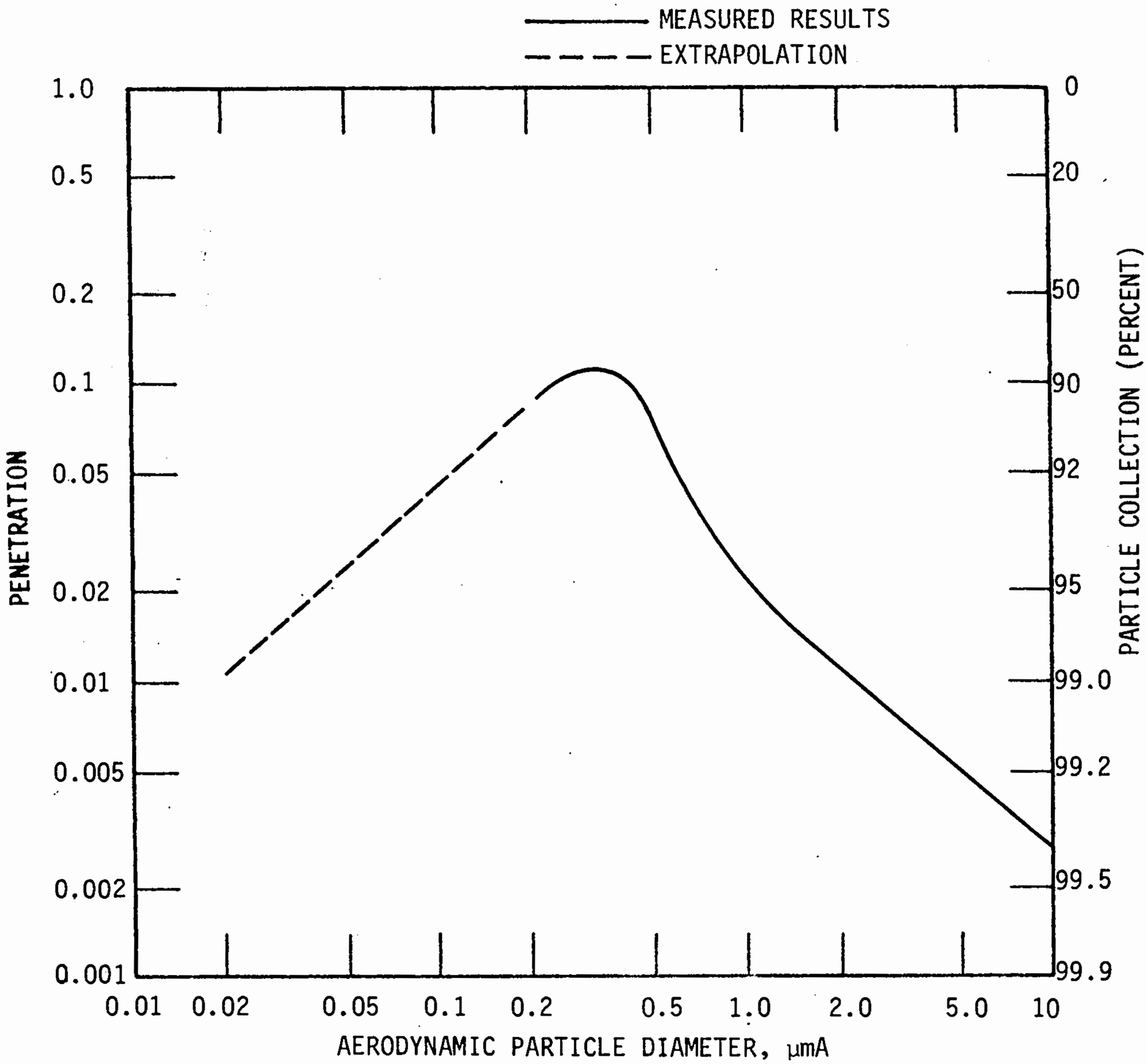


Figure 8-4. TRW charged droplet scrubber fractional efficiency performance.[3]

TABLE 8-1. CDS DESIGN SUMMARY[3]

- Three high-voltage scrubbing stages with 0.127-m collector plate spacing.
- Flow cross-sectional area, 7.36 m^2.
- High-voltage electrode, type 316 stainless steel tubing, 19 mm diameter flattened to 12.7 mm.
- High-voltage electrodes contained 67 spray tubes each on 44.5-mm centers.
- Spray tubes, titanium with 1.27-mm O.D. by 0.15-mm wall, protruding 25.4 mm from the electrode.
- Collector plates 3.05 m long, 1.83 m high, 2.0 mm thick, mild steel.
- Wall wash system covering each collecting surface.

droplets then flows into a mist eliminator consisting of a positively charged corona section that removes the entrained droplets.[4] The UWEDS system is shown schematically in Figure 8-5.[5]

Pilot plant studies were conducted with a UWEDS mobile unit on an electric arc steel furnace and a coal-fired power plant. Overall collection efficiencies ranged from 79.7 to 99.6 percent on steel furnace emissions and from 99.6 to 99.99 percent on power plant emissions under various source and control device operating conditions. Fractional efficiency ranged from 90 to 99.99 percent for fly ash particle sizes of 0.3 to 10 μm (Figure 8-6).[6] Further results from the power plant tests indicate that the UWEDS system operates with a specific collection area from 9.8 to 13.3 m^2 per m^3/s, and with water consumption from 2.0 to 2.1 liters/m^3. Total power consumption is estimated at 0.8 kW per m^3/s.[5] No data have been published on annualized costs for a full-scale system.

8.1.4 Steam Hydro Scrubber (SHS)

The Lone Star SHS system uses high pressure steam to move the gas through the system, and to enhance particle collection with flux/force condensation (F/C). (F/C effects are discussed in Section 8.1.6 .) The fast-moving steam entrains gas, particles, and water droplets within the mixing tube, where particle/droplet collision occurs. The mixing tube

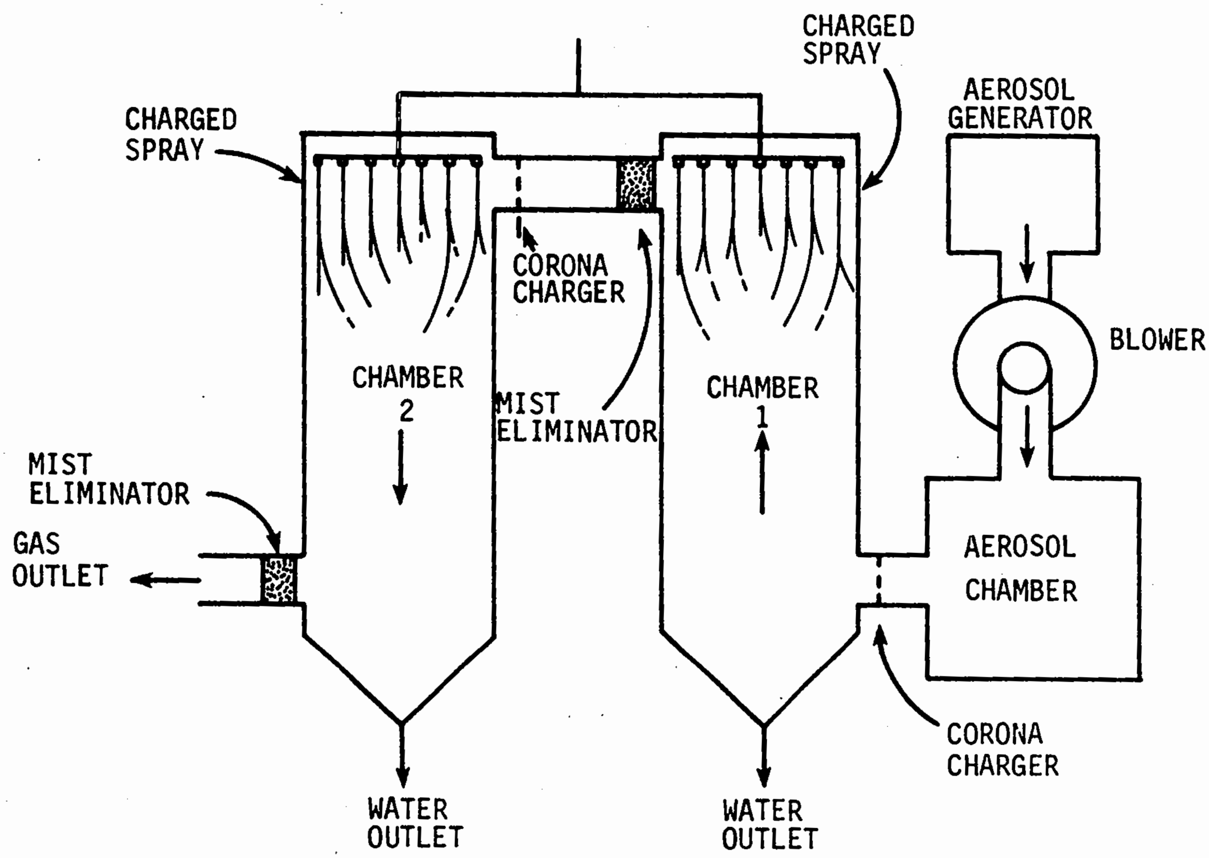


Figure 8-5. University of Washington electrostatic droplet scrubber schematic.[5]

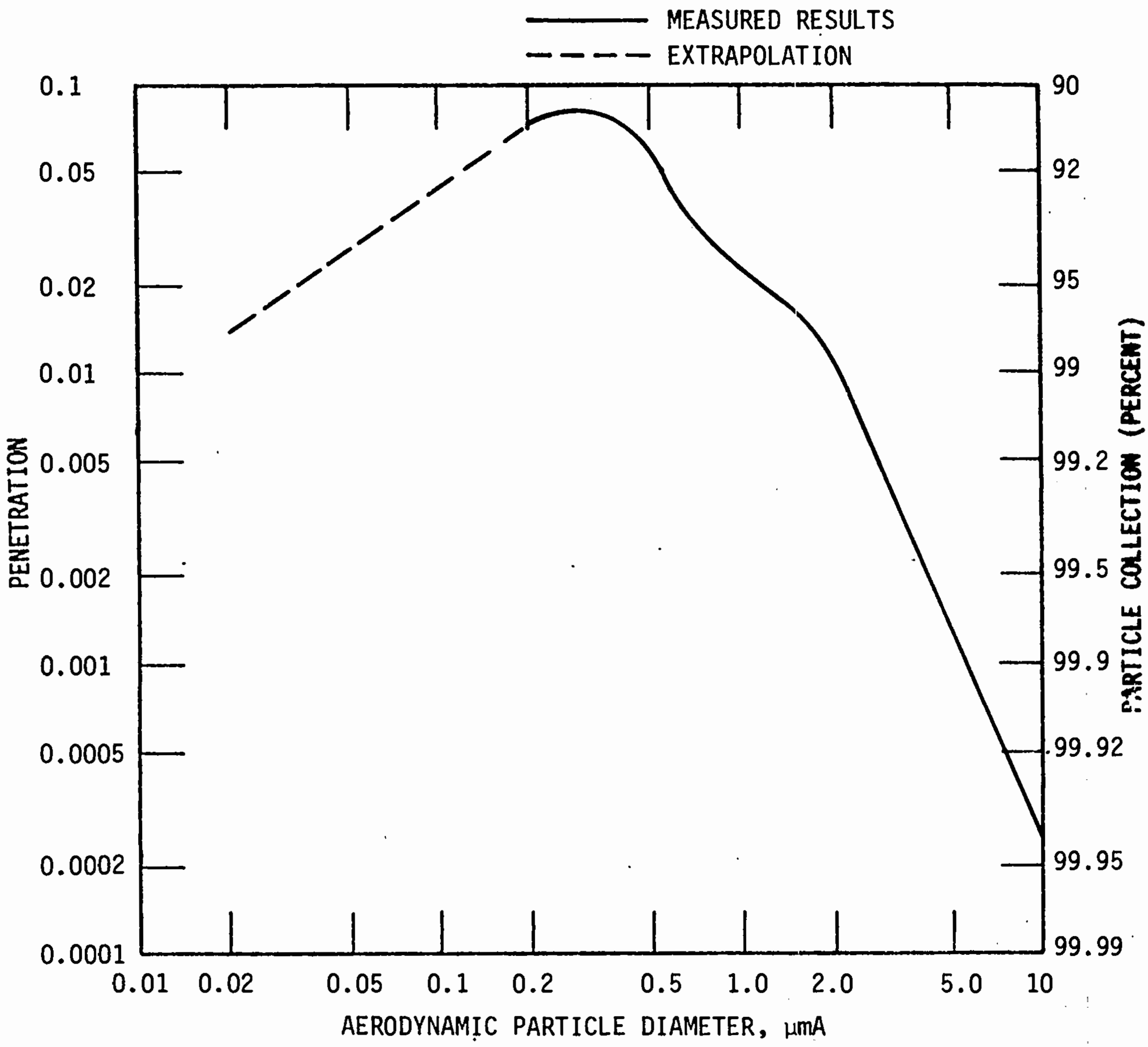


Figure 8-6. University of Washington electrostatic droplet scrubber fractional efficiency performance.[6]

promotes particle/droplet collision through inertial and F/C collection mechanisms. A shock-wave pattern is created in the mixing tube, further enhancing particle/droplet collision by the induced turbulence. Upon exiting the mixing tube, the stream is accelerated to achieve more complete separation of the entrained materials in the cyclones. Centrifugal mechanisms in the low-pressure-drop cyclones account for the impingement and separation of the aerosols entrained from the gas stream. The SHS system is depicted in Figure 8-7.[7]

A performance evaluation was conducted on a commercial SHS system of 6.1 m^3/s capacity controlling an open-hearth furnace.[7] Overall collection efficiency was measured from 99.78 to 99.95 percent under different source and control device conditions. Fractional efficiencies ranged from 70 to 99.99 percent for particle sizes from 0.02 to 10 μm under different conditions (see Figure 8-8). Estimates of total power consumption indicate 395 kW per m^3/s if waste heat is not available, and ~0 kW per m^3/s if waste heat is available for use as steam.[5]

8.1.5 Two-Phase Jet Scrubber (TPJS)

The Aeronetics TPJS system uses a nozzle designed to produce a two-phase mixture of vapor and liquid droplets when fed pressurized, heated liquid. The droplets are initially accelerated by the pressurized delivery and become further accelerated by expansion due to evaporation of the hot (200°C) water. Calculations by the developers indicate that the droplets attain supersonic velocities (~300 m/s). The intense atomization and relatively high droplet velocity produce a high probability of collision with entrained particles. With typical droplet diameters (<100 μm) at the indicated supersonic velocity, the impaction mechanisms would be effective for particles as small as 0.2 μmA diameter.[5] An additional benefit of the TPJS system is an induced draft, which eliminates or minimizes fan power requirements. Figure 8-9 is a schematic showing two options of the TPJS system.[8]

Performance evaluation of a commercial TPJS system was conducted at a 7.5-MW_e submerged arc ferro-alloy furnace.[8] Average overall collection efficiency was 95.9 percent under typical furnace and scrubber operating conditions. Fractional efficiencies covered a wide range: 30 percent removal of particles in the 0.03 to 0.10 μm size range and ~99 percent for

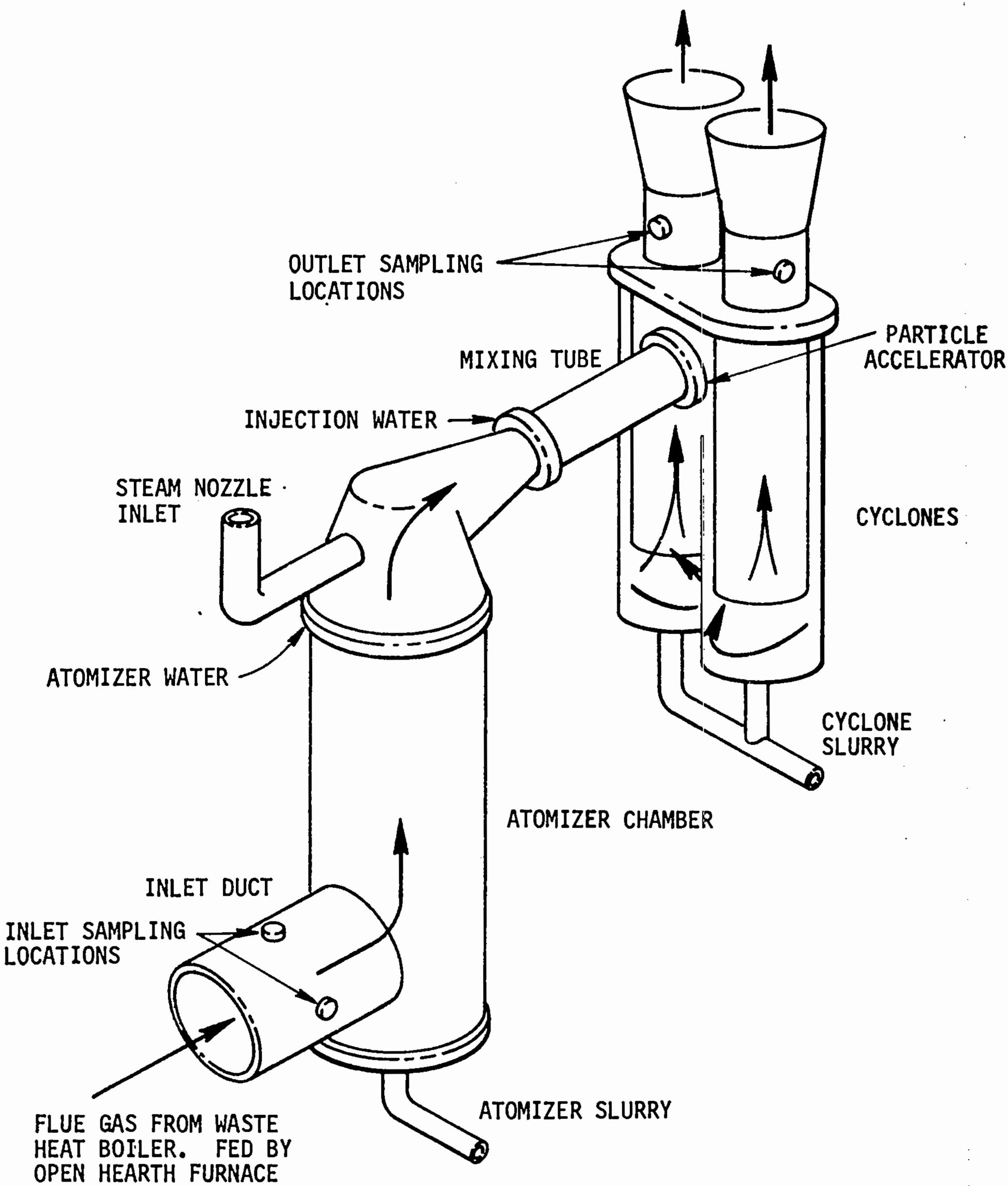


Figure 8-7. Lone Star Steel steam-hydro air cleaning schematic.[7]

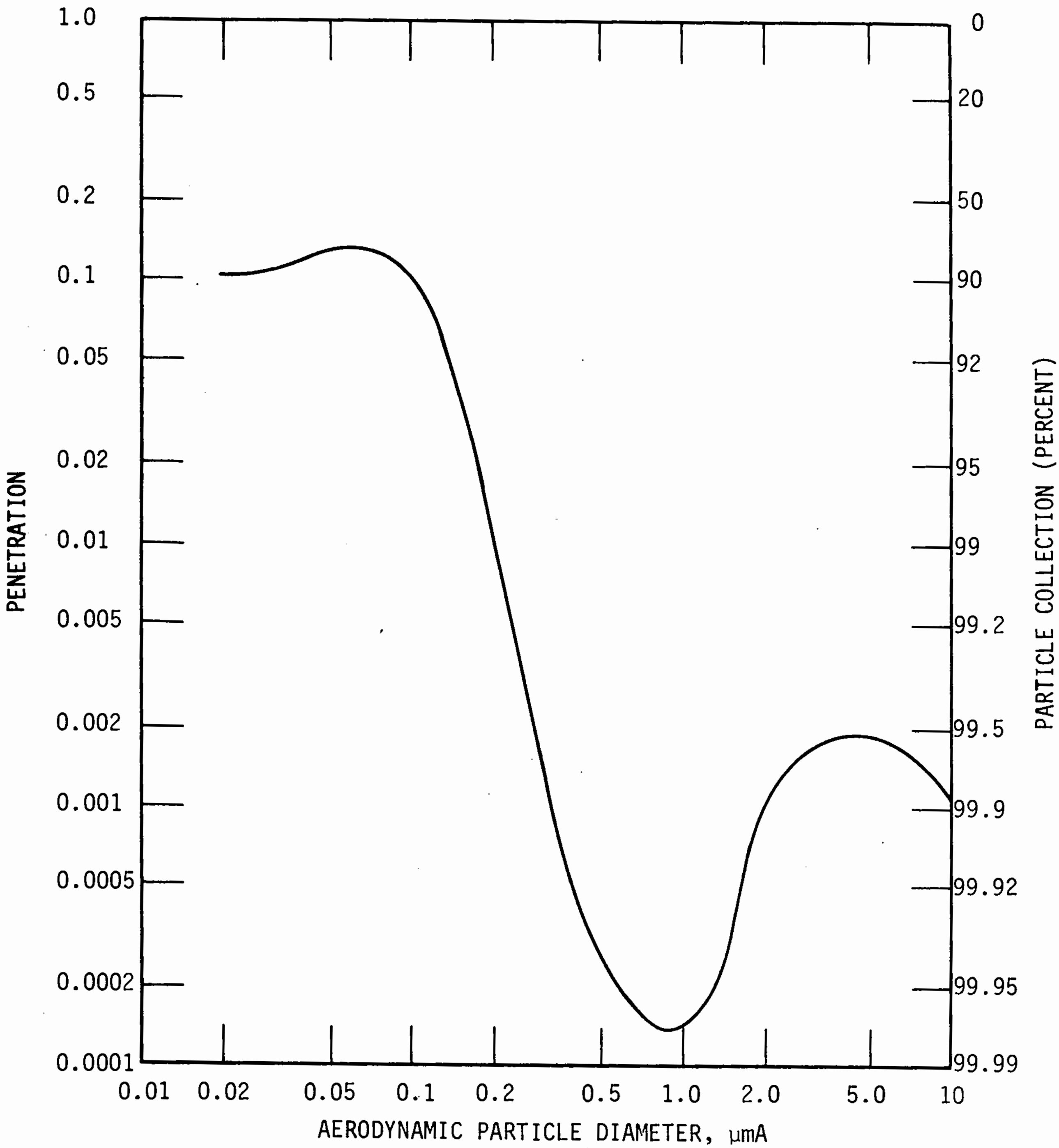
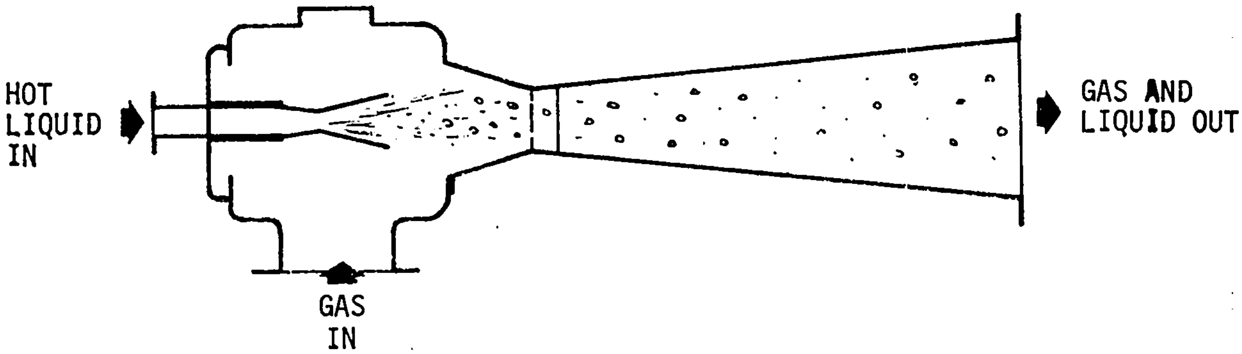
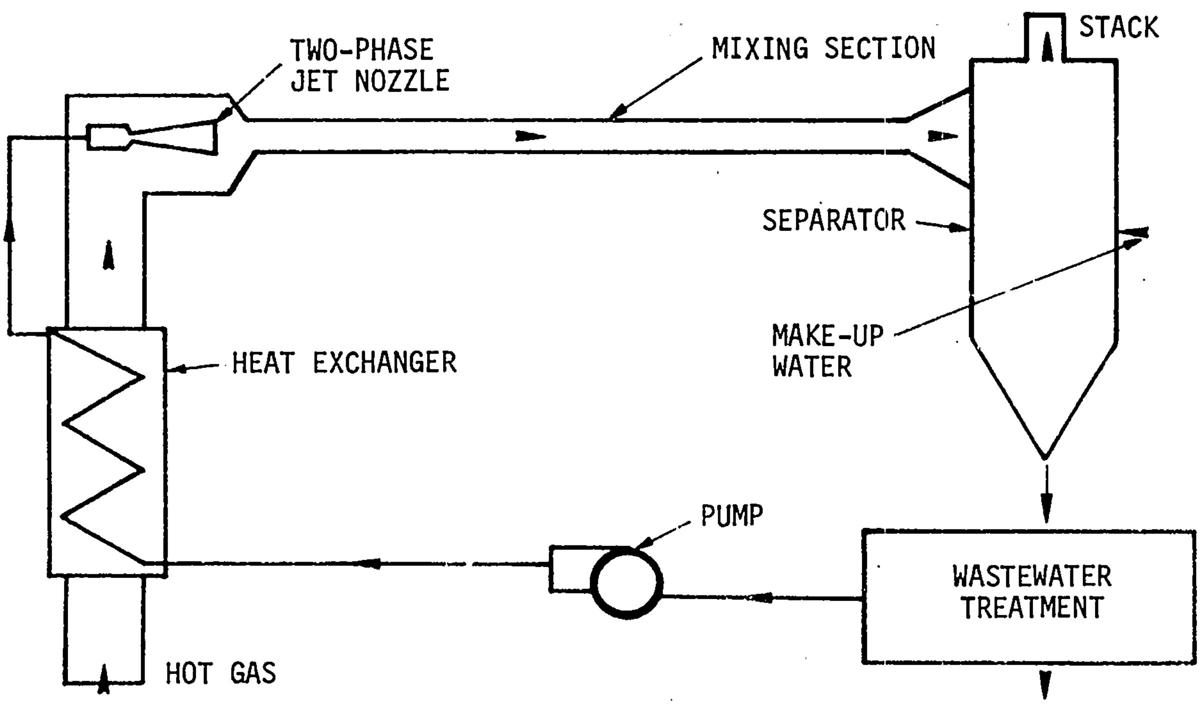


Figure 8-8. Lone Star Steel steam-hydro air cleaning fractional efficiency performance.[7]



OPTION 1



OPTION 2

Figure 8-9. Aeronetics two-phase jet scrubber schematic.[8]
(2 options shown)

those in the 0.5 to 10 μmA range (see Figure 8-10).[8] Estimates of total power consumption are 41 kW per m^3/s if waste heat is not available and 3.8 kW per m^3/s if waste heat is available for use as steam.[5]

8.1.6 Flux Force/Condensation Scrubbing

Flux force/condensation (F/C) effects are those that accompany the condensation of water vapor from a gas stream; they are generally caused by contacting hot, humid gas with colder liquid and/or by injecting steam into saturated gas. Flux force/condensation also capitalizes on the growth of particle mass and size due to condensation of water vapor on suspended particles. Particle growth facilitates the collection of particles by inertial impaction. In practical terms, F/C scrubbing takes advantage of forces acting on the particles induced by a temperature gradient (thermophoresis), a vapor condensation gradient (diffusiophoresis), and vapor condensation (Stefan flow). This advanced scrubbing method is adaptable to various scrubber configurations; the ability to enhance particle collection has been demonstrated with venturi, sieve plate, packed bed, and mobile bed designs.[9,10] Moreover, as particle size decreases, the advantages of F/C scrubbing over conventional systems becomes greater because F/C collection efficiency is virtually independent of particle size.

A demonstration F/C scrubbing system was built consisted of a spray-type quencher, a sieve plate column, and a spray-type cooling tower with an induced draft fan.[11] The demonstration was performed on a secondary metal-recovery furnace emitting particles with a mean aerodynamic diameter of 0.75 μmA. The 12,000-m^3/h demonstration system collected 90 to 95 percent of the submicron stream at a pressure drop of 68 cm W.C. Under these source conditions, a conventional high-energy scrubber would require pressure drops of approximately 250 cm W.C. for 90 percent collection efficiency and 535 cm W.C. for 95 percent.

8.2 ADVANCED ELECTROSTATIC PRECIPITATION TECHNIQUES

Conventional electrostatic precipitators often cannot effectively treat particulate materials that have high electrical resistivity (i.e., greater than 5×10^{10} ohm-cm). The difficulty arises from the presence of highly resistive material on the collection surfaces and from the current density

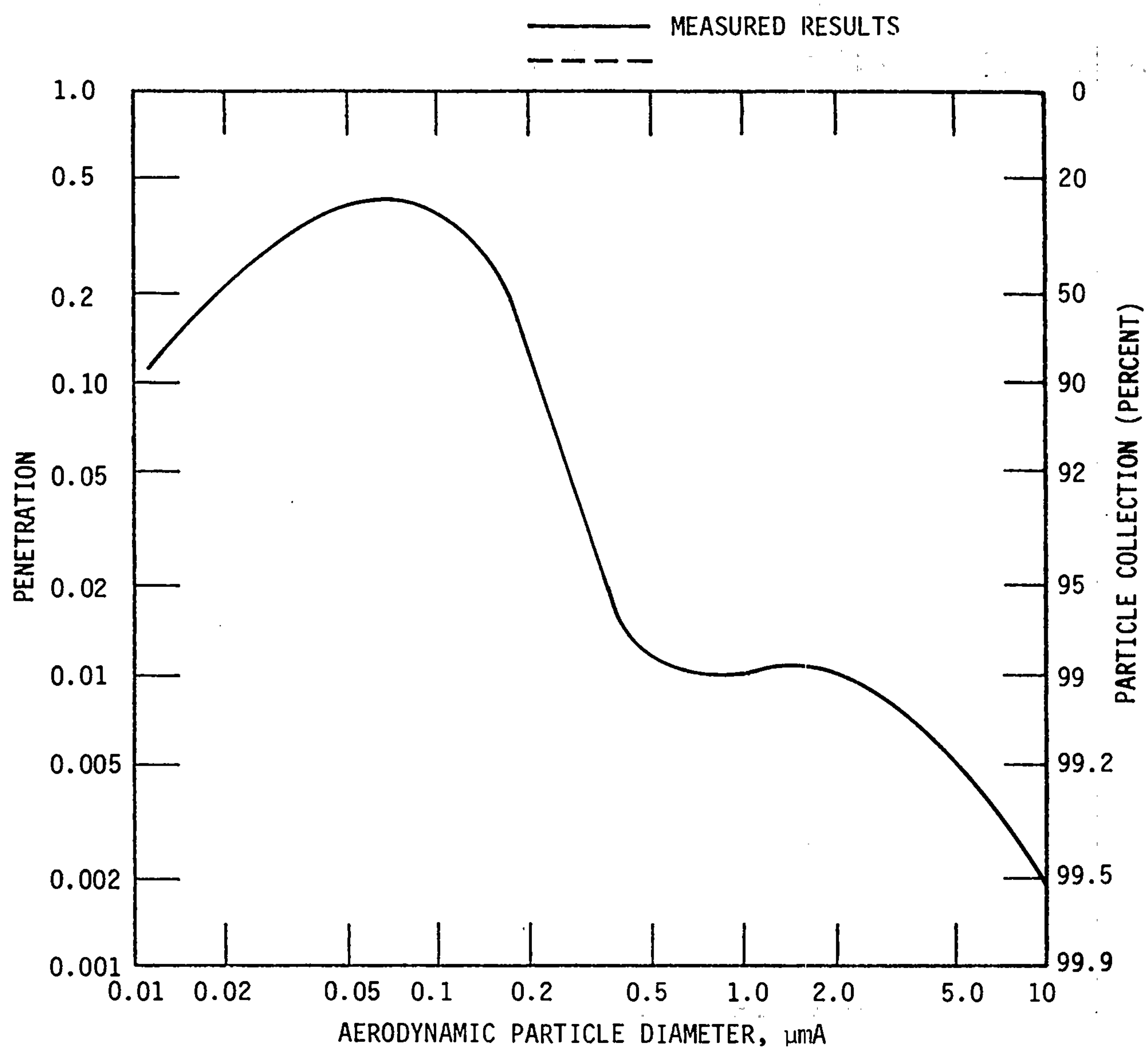


Figure 8-10. Aeronetics two-phase jet scrubber fractional efficiency performance.[8]

levels typical of conventional precipitators. In the collected dust layer the electric field strength, determined as the product of the resistivity and current density, may exceed the dielectrical strength of the material and cause electrical breakdown. This breakdown generally leads to conditions that cause the production of positive ions from the collected material. These ions have the reverse polarity of the ions discharged from the corona wires, and consequently they neutralize and degrade the intended charging process. This series of events stemming from the electrical breakdown is generally referred to as back corona or reverse ionization.

The difficulty of precipitating high-resistivity materials limits the performance of conventional precipitators. The following subsections discuss technologies that are being advanced as a result of and as a remedy for this difficulty.

8.2.1 Pulse Energization

The collection of high-resistivity dusts by conventional electrostatic precipitators can be substantially improved by pulse energization. The theoretical basis of the pulse concept was established over 30 years ago; in recent years, investigators in the United States, Europe, Australia, and Japan have developed this concept and brought it to the marketplace.

Pulses of appropriate duration and frequency superimposed on the DC voltage provide higher peak voltages, reduce sparkover, increase field and diffusional particle charging, improve current distribution, and permit independent control of secondary voltage and current.[12] Resistivity-limited dusts (e.g., those from combustion of some low-sulfur western coals) are more easily precipitated with pulse energization than by conventional means because higher and more uniform ion densities and field strengths prevail when the electrical limit is reached.

Pulsed energization systems superimpose a high-voltage impulse of very short duration and steep wave front on an underlying, relatively constant potential. This steady base voltage is maintained at a reduced level to sustain the migration of ions and particles toward the collecting plates. For treatment of high-resistivity dusts, the base voltage may be set below the normal corona initiation voltage. The high-voltage impulses momentarily raise the actual potential well above the sparking or back-corona limit that would be experienced with conventional energization.

Pulse frequency is set in the range of 10 to 400 pulses per second (pps). Higher secondary levels of peak voltage and current are achievable with progressively higher pulse frequency. Figure 8-11 shows current-voltage curves obtained with a special pulse-discharge electrode, illustrating the achievement of higher corona points at increasing levels of pulse frequency. Figure 8-12 shows current-voltage curves of conventional DC systems and pulse energization systems under the same conditions. The conventional current-voltage curve is steep, indicative of back corona, whereas the corresponding curve with pulse energization reflects higher operating voltage without back corona.

Limited but promising results on the performance and economics of pulse energization are now available in the literature.[13-16] Laboratory and pilot studies have steered this emerging technology into successful, short-term full-scale demonstrations. Full-scale applications on a 35 MW_e pulverized-coal-fired utility boiler[12] and a 290 ton/day rotary lime kiln[14] have demonstrated the performance and economic advantages of pulse energization in collecting high resistivity dust ($\sim 5 \times 10^{11}$ ohm-cm).

These two full-scale demonstrations were accomplished by retrofitting conventional ESP's with pulse energization electrical systems. Comparative tests on both emission sources were conducted with conventional DC power supply and a pulse generator. Results of collection efficiency measurements show a 1.3 to 1.5 factor of improvement by the pulse systems over the conventional systems.[12,14] The improvement factor was appropriately determined by taking the ratio of the modified migration velocity values calculated from the performance data for both systems, by use of the following modified Deutsch-Anderson equation:

$$P_t = \exp -(W_k\ A/V)^m \qquad \text{(Eq. 8-1)}$$

where

P_t = penetration

A = collection area, m^2

V = volumetric flow rate, m^3/s

w_k = modified migration velocity, cm/s

m = exponent, using a common value for m = 0.5.

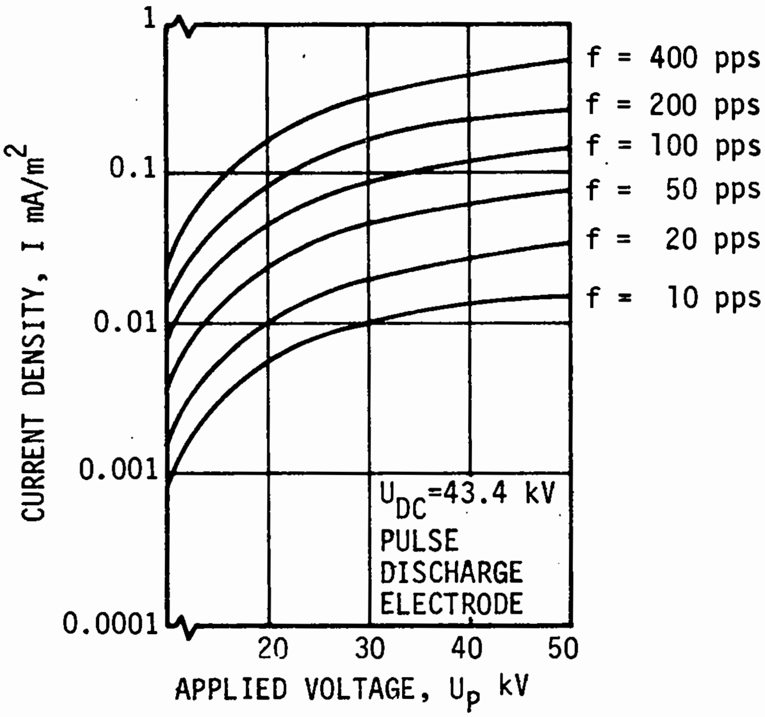


Figure 8-11. Pulse energization voltage-current relationships for various pulse frequencies.[12]

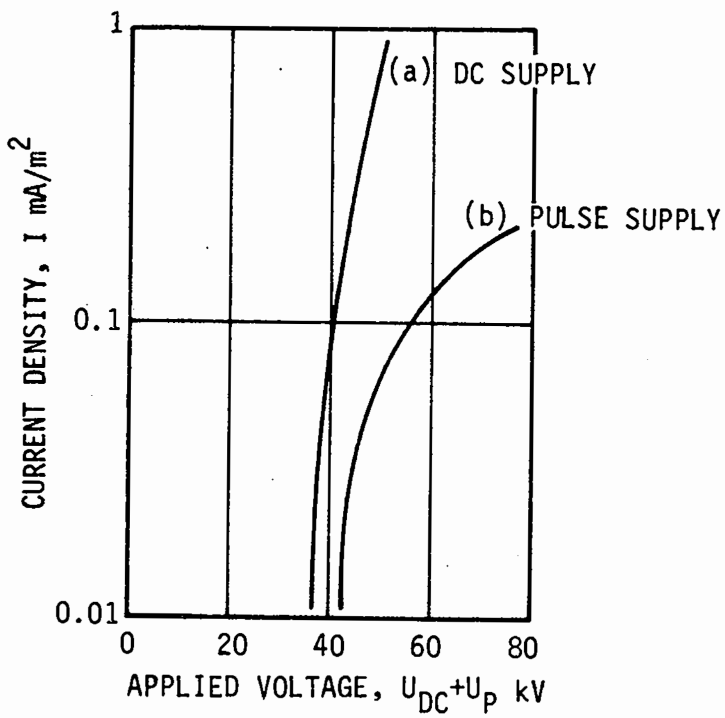


Figure 8-12. Comparison of DC and pulse energization voltage-current relationships with same discharge electrode.[12]

Additional indicators of the enhanced performance associated with pulse systems are a significant reduction in stack opacity and spark rate, and a large increase in peak operating voltage, both relative to performance of the conventional systems.

With respect to potential applicability of pulsed energization systems, the following should be kept in mind: 1) the reported improvement factors represent a substantial reduction in precipitator size, but the pulsed systems require more sophisticated and expensive electrical hardware; 2) the pulse energization system will consume more electrical energy unless the design incorporates an energy-conservation system; 3) the reported results are limited and may not be representative of all applications; and 4) further development and long-term demonstrations are needed for this emerging control technology.

8.2.1.1 Japanese Pulse Charging Systems. Further development of the pulse energization concept has occurred in Japan. A "Bias-Controlled Pulse Charging System" with a three-electrode configuration has been successfully demonstrated on large-scale ESP's.[16] This three-electrode configuration and bias-controlled pulse charging extend the applicable limit of precipitators to collection of dusts with resistivity up to 10^{15} ohm-cm. This novel system also provides advantages in system stability (reducing process variations and upsets) and flexibility over a wide range of conditions. The three-electrode system has also been applied to a 240 ton/h boiler plant emitting low-resistivity, finely dispursed carbon particles. The reliability and versatility of the three-electrode bias-controlled system have been demonstrated since 1976 on a space charge limiting exhaust at about 97 percent efficiency. Another novel system was installed in early 1978 to treat an 11,000 m^3/min exhaust from an iron-ore sintering furnace. With dust resistivities ranging from 10^{11} to 10^{13} ohm-cm, a quasi-pulse ESP system successfully collects 99 percent of the particulate emissions.[16]

8.2.1.2 Other Japanese Developments. Another Japanese development in ESP technology is the use of wide-electrode spacing design (50 to 60 cm). This design requires less plate area and allows operation at voltages approaching 200 kV. Full-scale wide-spacing ESP units have been used to effectively limit sinter plant emissions to less than 0.05 g/m^3 at resistivity levels in the range of 10^{11} to 10^{13} ohm-cm.[17]

Roof-mounted precipitators have been successful in the economical and space-effective control of blast furnace emissions from steel plants. The design includes vertical flow to allow natural convection for gas draft, collecting electrodes made from conducting plastic plates, and intermittent water irrigation.[18] Collection of materials with resistivities in the range of 10^{11} to 10^{12} ohm-cm is maintained at 95 percent efficiencies, and operating costs are 14 percent of those of a baghouse treating the same effluent.

8.2.2 Two-Stage ESP Precharging

One approach to the problem of precipitating high-resistivity materials is to separate particle charging from particle collection in a staged manner. A two-stage system is being developed by Southern Research Institute (SoRI) through sponsorship by the U.S. EPA.[19] The SoRI system incorporates a precharger with a novel electrode configuration and energization technique in the first stage (Figure 8-13), and a downstream collector with a novel corona discharge geometry in the second stage.

The first stage is similar to a conventional wire-to-plate design, but has an additional (screen) electrode to control back corona. The additional electrode consists of an open screen plate located close (1.9 cm) and parallel to the collection plate. Operation of the first stage is similar to that of a conventional ESP section, with the additional electrode being energized separately. The screen electrode is energized with the same polarity, but at a reduced voltage relative to the conventional discharge electrode. The downstream collector is also similar to a typical ESP, except that an open-mesh wire screen is used as a corona discharge electrode.[19]

In operation of the first stage, particle charging is effected in the usual manner, positive ions are produced, and then they are captured on the screen electrode before they drift into the active charging region. The screen electrode does not effect particle charging, but simply collects the positive ions being produced from the collected highly resistive material. The biased negative potential of the screen electrode assures capture of the positive ions, and with the openings in the screen electrodes allows passage of the negatively charged ions and particles to the plate.

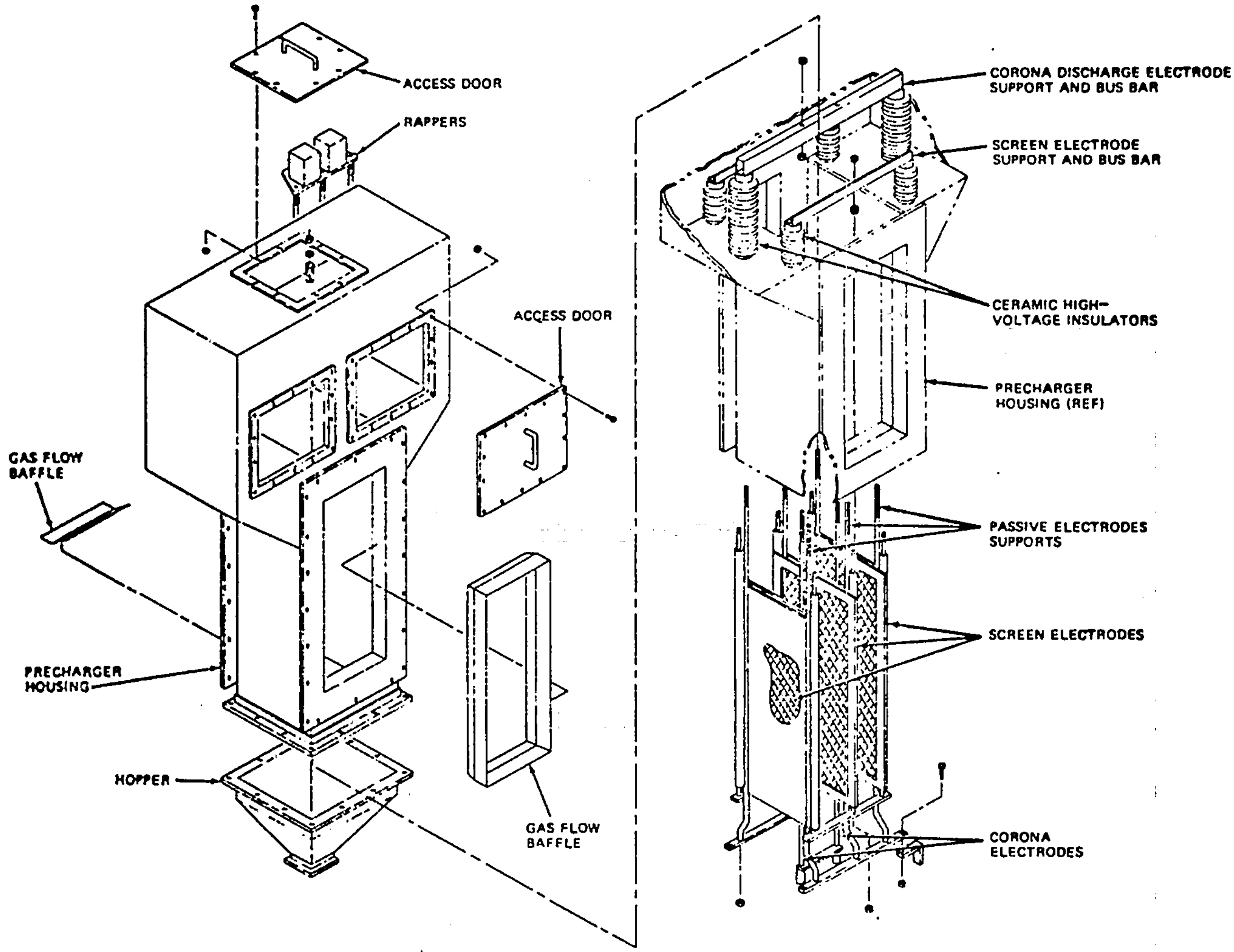


Figure 8-13. Southern Research Institute precharger ESP assembly drawing.[19]

Operation of the second stage is relatively conventional. The open-mesh wire screen electrode was selected on the basis of laboratory experiments to produce low current density with high electric field strength values. Since particle charging is essentially completed in the first stage, current levels are reduced in the second stage to minimize back-corona formation and reentrainment of collected material.

Laboratory studies and pilot field tests with this design have produced results that correlate with theoretical predictions. A field test with a 0.47 m^3/s pilot-scale device was conducted on a utility boiler burning low-sulfur coal and producing fly ash with a resistivity level measured at 2.0×10^{11} ohm-cm at 135°C.[19] Performance measurements on the pilot two-stage system showed an averaged collection efficiency of 97.7 percent, with specific collection area equal to 50.4 m^2 per m^3/s. In performance tests with the precharger off, emissions were seven times greater than with the precharger on. Parallel testing with a mobile, pilot system of conventional ESP design operating under the same conditions indicated a collection efficiency of 91.9 percent. The penetrating emissions from the pilot conventional system were 3.5 times those from the two-stage system. Fractional efficiency data indicate 70 to 98 percent collection of particles in the size range of 0.02 to 10 μmA (Figure 8-14).

The cost of fabricating such a two-stage system is estimated to provide a savings of approximately 40 percent over costs of a conventional ESP for control of high-resistivity material.[19]

8.2.3 Flue Gas Conditioning for ESP's

Flue gas conditioning involves the use of additive materials to control particle resistivity for the purpose of improving precipitator performance.[20] Conditioning agents may also enhance performance by altering non-electrical characteristics of the flue stream (e.g., particle agglomeration and/or adhesion). Conditioning can be considered as a control of particle resistivity, and includes three general means for control: particulate composition, flue gas composition, and temperature. The combination of these three factors accounts primarily for the resistivity levels associated with electrostatic precipitation. Secondary factors to be considered in suspected resistivity-related precipitator problems are thickness of the

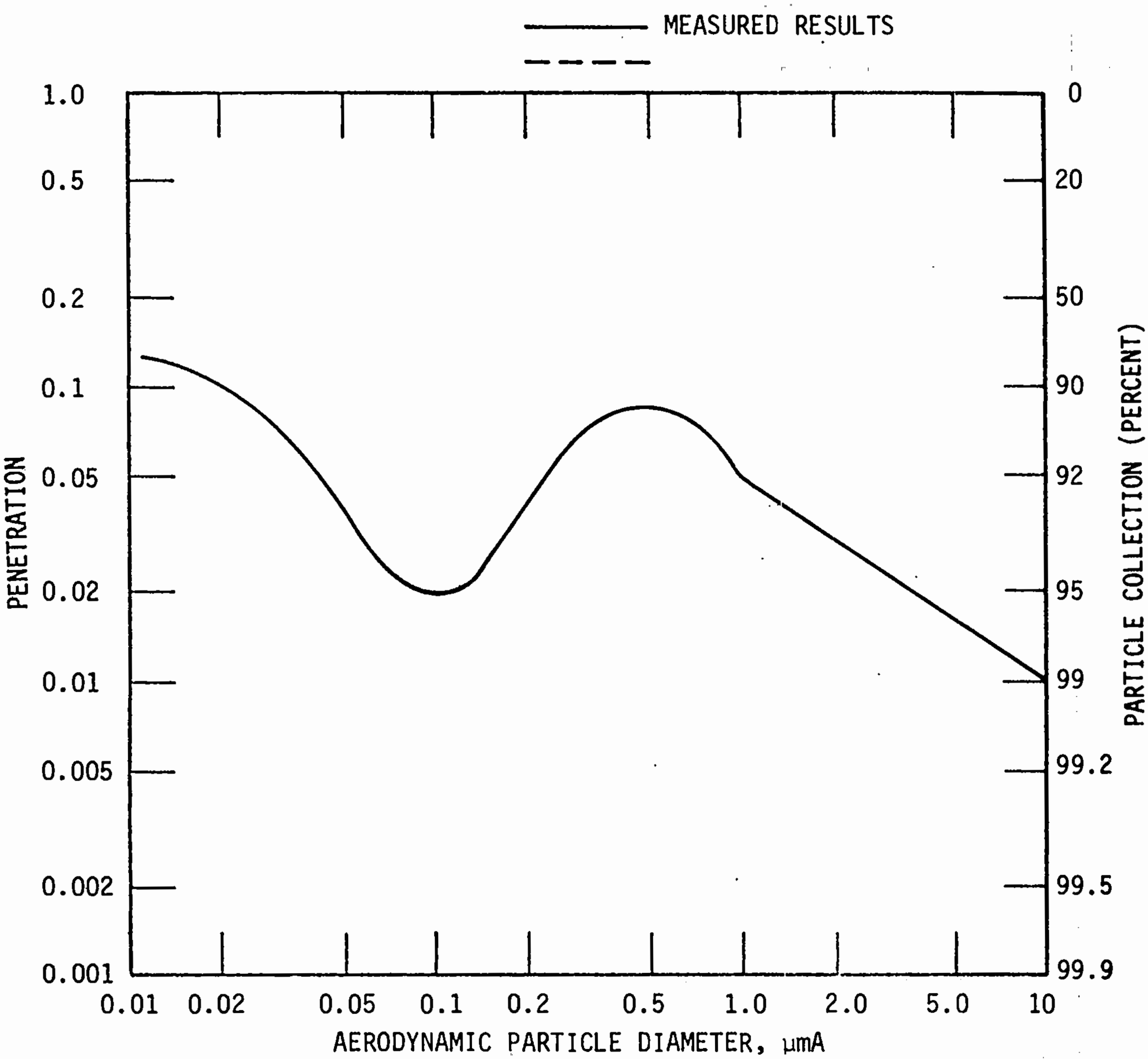


Figure 8-14. Sourthern Research Institute precharger ESP fractional efficiency performance.[19]

collected dust layer, the influence of electric field strength, and dust aging characteristics.

This section describes the more popular means of flue gas conditioning as indicated in published case studies. Gas conditioning is not a new concept, but is considered here as an emerging technology for two principal reasons: (1) gas conditioning is a cost-effective and attractive option for a growing number of new and retrofit ESP installations; and (2) the applicability and effectiveness of a conditioning agent or other means of conditioning can only be verified on an experimental, site-specific basis, and not by predictive or referencing techniques.

8.2.3.1 SO_3 Conditioning. The ultimate use of gas-phase SO_3 in streams from utility boilers or from other industrial processes fired with low-sulfur coal is becoming a popular, nonproprietary form of gas conditioning. Several commercial means of producing gaseous SO_3 include (1) use and combustion of elemental sulfur with appropriate processing, (2) use of SO_2 with catalysis to form SO_3, and (3) purchase and direct use of SO_3. Capital investment, operating cost, system reliability, and safety considerations are the main determinants in selecting an SO_3 conditioning system. Injection of trace quantities of SO_3 (3 to 30 ppm) in the gas stream is cost-attractive and effective in reducing resistivity by 1 to 2 orders of magnitude for ESP temperature conditions less than 200°C.

Results of an SO_3 conditioning study[21] of an ESP-controlled utility boiler burning 0.6 percent sulfur coal showed an improvement of overall collection efficiency from 91.3 to 98.8 percent. Upon injection of 25 ppm of SO_3 particulate emissions were reduced by a factor of 8.3, measured resistivity dropped from 6×10^{12} to 4×10^{10} ohm-cm at 143°C, and emission of H_2SO_4 vapor (<1 ppm) was the same as without conditioning. This successful SO_3 injection reduced particulate emissions in an amount equivalent to expanding the existing ESP capability by a factor of about 3.

Another study[22] on utility boiler burning low-sulfur coal also demonstrates the effectiveness of SO_3 conditioning on precipitator performance. In this installation SO_2 is catalytically converted to SO_3 and injected downstream of the air preheater at a rate corresponding to 32 ppm of SO_3 in the flue gas stream. Stack measurements with the controlled condensation method indicated SO_3 concentrations of 10.9 and 8.1 ppm at the ESP inlet and outlet, respectively. Mass loading measurements indicated that SO_3 conditioning reduced particulate emissions by a factor of 2.4, corresponding to an increase in collection efficiency from 79.2 to 95.4 percent relative to baseline conditions without SO_3 injection.

Other case studies of SO_3 conditioning illustrate the effectiveness and limitations of this method. Many cost estimates for new utility installations include SO_3 conditioning as an alternative control method. At least two U.S. vendors of ESP's have indicated that the combination of a cold-side precipitator with SO_3 conditioning is the most cost-effective method for control of boilers burning low-sulfur western coal.[23-25] Cost analyses show savings of 20 to 80 percent in annualized costs for gas conditioning with conventional (cold) precipitators, relative to the costs of nonconditioned cold precipitators, hot precipitators, and baghouses.[26]

8.2.3.2 Gas Conditioning With Water-Soluble Alkali Compounds. Certain water-soluble alkali salts have been shown to be effective conditioning agents in certain industrial processes. Laboratory experiments and full-scale demonstrations show a sensitive relationship between resistivity and the content of water-soluble alkali compounds in the collected material. The following paragraphs deal with case studies in which potassium sulfate, sodium chloride, and sodium carbonate are used as conditioning agents. Note, however, that the descriptions of these materials as conditioning agents do not imply that they are universally applicable conditioning agents, effective on any given resistivity-limiting process stream. Rather, the discussion of these agents, which are natural, common, and/or inexpensive, is meant to indicate the sensitive relationship between resistivity and trace quantities of readily available materials, and the resultant impact on precipitator performance.

Potassium sulfate (K_2SO_4) was demonstrated as an effective, conditioning agent on an 800-ton/day cement kiln process in Brazil.[27] The K_2SO_4 was mixed in water as a 5 percent solution, then injected, atomized, and evaporated in the gas stream ahead of the precipitator. The K_2SO_4 solution was injected at a rate of 500 liters/h, a negligible (0.02 percent K_2O) amount compared with the normal content of this constituent (0.4 percent K_2O) in the raw meal. Performance measurements showed an increase in overall collection efficiency from 75.0 to 86.7 percent because of conditioning, corresponding to a twofold reduction in particulate emissions. Resistivity measurements indicate a reduction from 10^{13} to 10^{11} ohm-cm at 300°C, attributable to K_2SO_4 conditioning.

Another full-scale demonstration with K_2SO_4 was conducted successfully on a coal-fired lime kiln in South Africa.[27] A separate and parallel demonstration was made with sodium chloride.[27] Each conditioning additive was put into solution in the cooling water injected into the kiln. The results of adding these materials were an increase in water-soluble K_2O from 0.02 to 0.25 percent, and an increase in water-soluble Na_2O from 0.04 to 0.27 percent, in the precipitated dusts. Each conditioning agent reduced particulate emissions by a factor of 4 and resistivity by 2 orders of magnitude. Note that sodium chloride was an effective agent for this process, but may not be applicable in other industries because of incompatibility with the process, product, or materials of construction.

Sodium carbonate has been used as a conditioning agent for hot-side ESP's on at least two boilers fired with low-sulfur coal.[28] At one installation, a 15 percent solution of Na_2CO_3 is used as the conditioning medium; at another, the conditioning agent is commercial-grade soda ash, which is pulverized and fed pneumatically into the process stream as a dry material. Both sodium carbonate systems are used to condition process streams in the temperature range of 370° to 400°C, which is the range of the ESP treatment. Particulate emissions have reportedly been reduced by a factor of 20 by conditioning with Na_2CO_3 solution and by a factor of 9 with solid Na_2CO_3.

8.2.4 Development of High Temperature/High Pressure (HTHP) Electrostatic Precipitation

Concern over the feasibility of high temperature/high pressure (HTHP) electrostatic precipitation arose as technological developments in advanced energy-producing processes indicated the need for HTHP cleanup systems. A recent laboratory study of the characteristics of electrostatic precipitation at high temperatures and pressures has yielded substantial and encouraging conclusions.[29]

Bench-scale experiments with a concentric wire-pipe ESP design were conducted at temperatures up to 1100°C (2000°F) and pressures up to 3550 kPa (515 psia) with both negative and positive polarity energization.[29] The experimental program included the use of three gas mixtures: dry air, a simulated flue gas, and a substitute (noncombustible) fuel gas. The experimental results indicate higher particle-collecting efficiencies under conditions of high temperature and pressure than those usually achieved with conventional precipitator design and conditions. Higher operating voltages are obtainable and are stable over the broad temperature/pressure range of practical interest. These higher voltages provide increased electric field strengths and promote higher probability of particle collection.

Experimental results demonstrate that potentially higher breakdown voltages are achievable with the combination of high temperature with appropriately high pressure. Concerns about achieving stable corona are resolved with the understanding of a "critical pressure" concept. The critical pressure is the lowest level of elevated pressure at which corona initiation and sparkover voltage levels coincide. Increasing the temperature raises the critical pressure for achieving stable corona and consequently broadens the operating pressure range. The general rule is that high pressure should accompany high temperature. Failure to operate at or above the critical pressure level will result in sparkover or breakdown without the necessary corona formation.[29]

The critical pressure concept is applicable to both positive and negative polarity systems. With positive discharge systems, this critical phenomenon is distinct and reproducible. With negative discharge systems the pressure limit is not so well-defined, but the systems generally respond to application of the critical pressure concept. At high gas densities, higher operating voltages are achievable with negative than with positive discharge.[29]

8.3 ADVANCED FILTRATION TECHNIQUES

Filtration technology is being advanced through incorporation of electrostatic designs, new filtration media, and novel filtration concepts. Research has shown that natural or induced electrostatic phenomena can play a critical role in the operating and collection performance of conventional filtration systems. Current studies are aimed at clarifying the effects of electrostatic charge and electric field on the collectibility and cleanability of conventional filter media. The advent of new filter materials is promoting the use of filtration technology to control process emissions to which conventional filtration has been inapplicable. High-temperature filtration, currently not economical above 300°C, is likely to become commercially available for elevated temperature control applications. Future requirements for control of high temperature/high pressure process streams are being evaluated with new filtration concepts and requisite new filtration media. Filters made from ceramic materials are currently being evaluated and developed for such applications. The following subsections describe these emerging filtration technologies.

8.3.1 Electrostatically Augmented Fabric Filtration

In electrostatically augmented fabric filtration, particles are precharged before crossing a fabric filter, which may or may not be electrostatically charged. Figure 8-15 shows a schematic of the pilot unit built by American Precisions Industries, Inc., called the Apitron. Air enters the precipitator section from below, then passes upward through the tubes of a set of parallel wire-pipe precipitators, in which the particles are charged and most are precipitated. The air then continues into and through the bags, where final filtration takes place. Bag cleaning is initiated by pulse jet flow. Studies on silica dust and various other particulate emissions[30,31] indicate that the Apitron yields high collection efficiencies (Figure 8-16) and that air/cloth ratios can be much higher than those in an uncharged filter of similar size. For example, a fabric filter utilizing a pulse jet cleaning mechanism might require an air/cloth ratio of 5 m^3/m^2-min whereas an electrostatically augmented filter operates at an air/cloth ratio of 14 m^3/m^2-min.[36]

8.3.2 Electrostatically Augmented Filtration Through Fiber Beds

The concept of electrostatically augmented fiber bed filtration was studied by Battelle Northwest on aerosols (NH_4Cl, Na_2O, and MgO) having mass mean diameters less than 1 μm.[32] The freshly generated particles were first

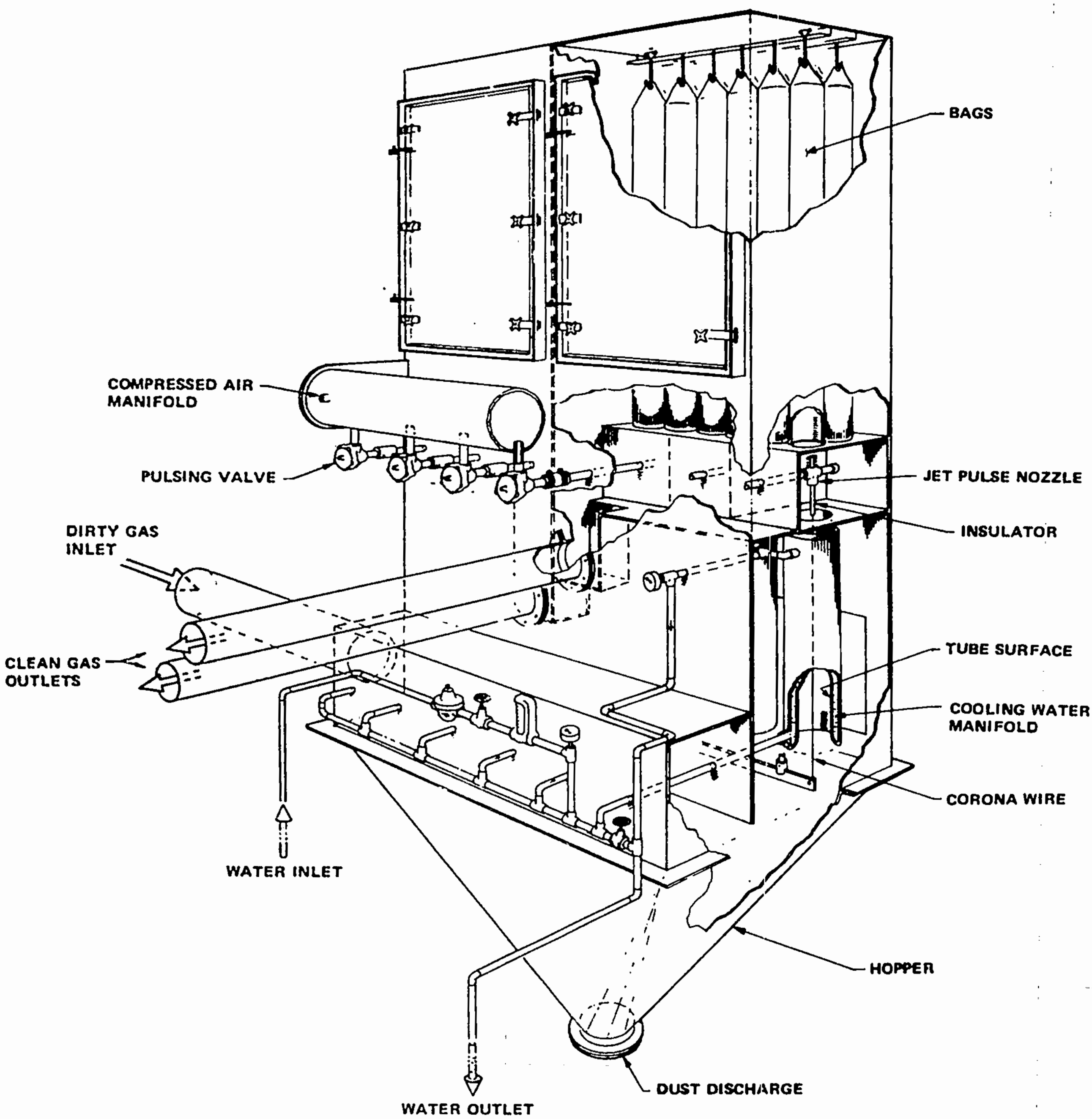


Figure 8-15. Apitron electrostatic-filter cutaway view.[35]

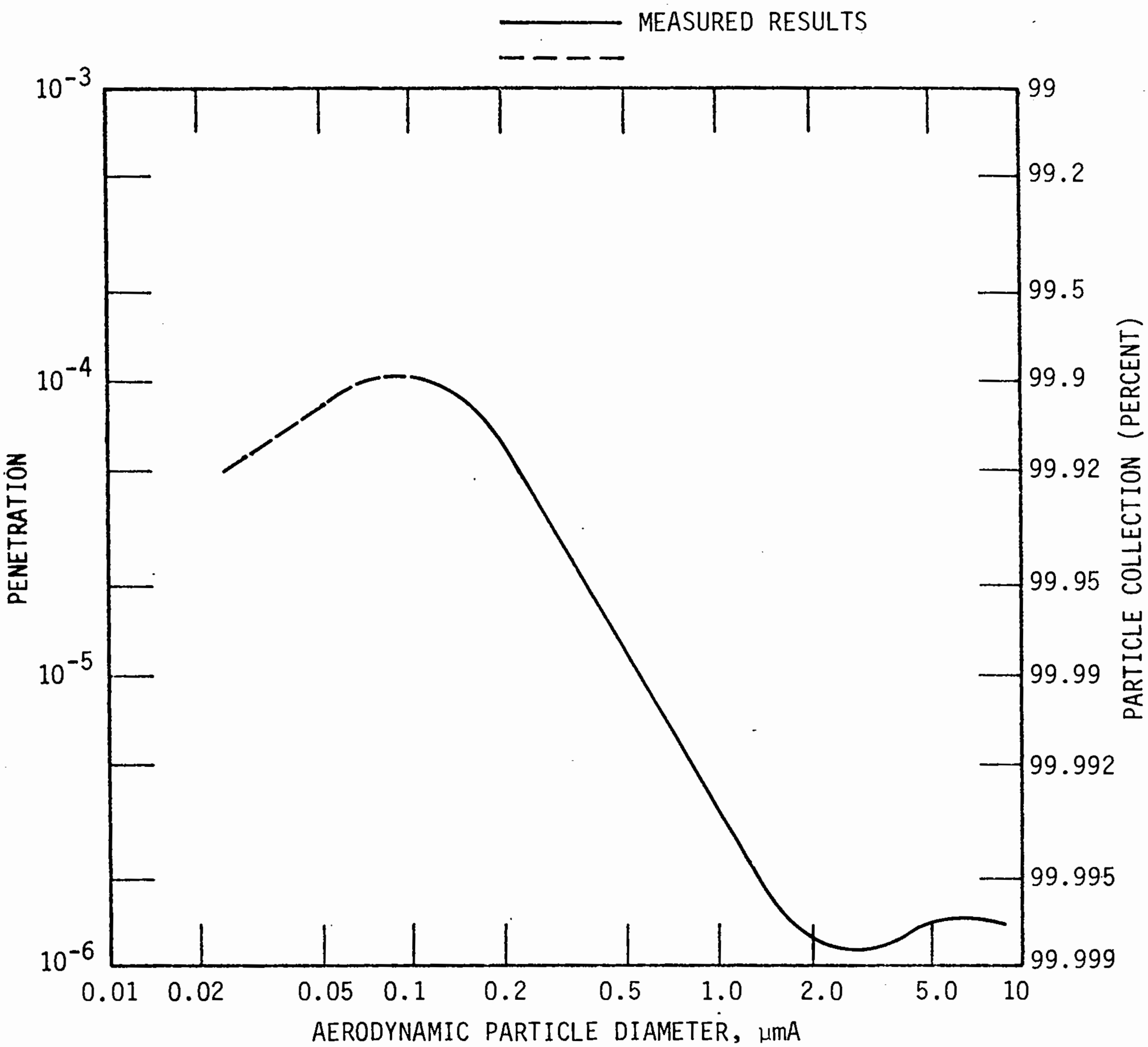


Figure 8-16. Apitron electrostatic filter fractional efficiency performance.[35]

drawn through a corona charging section and then through the fibrous beds, which were made of stainless steel, polypropylene, or Teflon^R and had a void fraction of 0.96. At velocities up to 1 m/s through a bed 30 cm thick, the collection efficiencies were greater than 95 percent and pressure drops were less than 1 cm H_2O.

8.3.3 Granular Bed Filtration

The general term "granular bed filtration" describes any filtration system including a bed of discrete granules or particles as the filtration medium. To prevent the particulate matter from plugging the interstices between granules and causing excessive pressure drop, the device must incorporate some means for periodic or continuous removal of particles from the collecting surfaces. Fixed-bed filters are cleaned periodically, generally by a backwash of air to blow the dust out of the bed. Moving-bed filters are cleaned continuously by replenishing the dirty bed with new granules and separating the dust and granules by vibration.

The primary mechanisms for particulate collection in a bed of granular solids are inertial impaction, flow line interception, diffusional collection, and gravity settling. Interception is the mechanism for particulate collection by gas convection, but collection by this mechanism is negligible with a clean bed. As particles are deposited in the interstices to form a cake, interception becomes increasingly important as the bed porosity and flow channels are reduced. When too much particulate matter is deposited, the pressure drop becomes excessive and the bed must be cleaned.

A series of studies was performed on the pressure drops and particulate collection efficiencies of 1.1-μm-diameter latex spheres at a superficial gas velocity of 50 cm/s.[33] The collection bed is made up of iron shot. With a bed depth of 3.2 cm at a gas velocity of 50 cm/s, the collection efficiencies are 22 and 53 percent for shot granules of 620 and 490 μmA diameter, respectively. Efficiency can be increased to nearly 90 percent as the bed depth increases, although with a significant increase in pressure drop. Performance data on removal of fine particles with granular bed filters are lacking for industrial applications, especially at high temperatures and pressures. Some preliminary studies on a pilot-scale fluidized bed combustion unit are inconclusive because of plugging of the filter and the retaining screens that hold the granular beds.[34] Combustion Power Company is just beginning a series of "cold" filtration experiments on moving granular bed filters, and results are pending.[35]

8.3.4 Barrier Filtration

Barrier filtration with fiber beds, woven fabrics, and porous materials can be used efficiently to remove particulates from gas streams. At high temperatures and pressures, however, special materials, usually ceramics, must be used to construct the bed matrix. Ceramic fibers can be woven into a fabric, packed into a mat, or made into sheets and then used to form filter "bags" comparable to those made of conventional fabrics. Their particulate removal characteristics are comparable to those of conventional barrier filters except that the ceramic material can withstand higher temperatures. Barrier filtration operates by three mechanisms of particulate removal: direct interception, diffusion, and inertial impaction.[36] Particle collection efficiency increases as a dust cake builds up on the filter. Collection efficiency can be improved simply by making a filter bed thicker (thus increasing the pressure drop) or by reducing fiber diameter.[37] Reducing fiber diameter is a desirable approach because it reduces filter weight and bed thickness.

Tests were performed with several ceramic media samples to determine penetration levels of dioctylphthalate (DOP) particles at air velocities of 5.5 and 16.5 cm/s under ambient conditions. The results indicated highest efficiency for paper media, intermediate for felts, and low for woven materials. Moreover, the efficiencies of many of the samples were higher for filtration of DOP smoke than were those of standard industrial-grade filters. Collection efficiencies of the woven ceramic materials were poor, probably because of their more open structure. Paper media in general had poor mechanical strength and did not survive pulse cleaning.

Initial screening and experiments indicate that "blanket" ceramic fiber materials (felts) consisting of small-diameter fibers (3 μmA) are the most promising because of their combination of good filtration performance and relatively high strength.[36] A filter was made of a layer of Saffil alumina blanket insulation material approximately 1 cm thick contained between stainless steel (304) screens. This configuration was tested with flyash from a pilot scale fluidized bed combustor. Tests were made over a period of 200 hours. High collection efficiencies (greater than 99 percent) were maintained with an air/cloth ratio of 9 m^3/m^2-min.[37] Further studies are needed to develop more efficient cleaning techniques, to maximize air/cloth ratios, and to further demonstrate the effectiveness and durability of such devices.

Porous ceramic filters are also under study.[38] The most promising configuration is a ceramic cross-flow monolith (ThermaComb) produced by the 3M Co. This material is composed of alternate layers of corrugation separated by thin filtering barriers. Limestone test dust with a mass median diameter of 1.4 mm was used to test the filter, and dust loadings were maintained at levels from 2 to 7 g/m^3. At linear velocities of 0.41 m/min, collection efficiencies were greater than 99 percent over a range of temperatures from ambient to 970°K. Thus, porous ceramic filters are viable as barrier filters, and their performance should be studied relative to that of ceramic fiber filters.

8.4 HIGH-GRADIENT MAGNETIC SEPARATION

Magnetic separation has long been recognized as a method of removing magnetic materials from mixtures, as in the separation of ferrous minerals from ores. Within the last decade, the development of high-gradient magnetic separation (HGMS) techniques has enabled the efficient separation of submicron particles of weakly paramagnetic materials from liquid streams at high process rates.[39] Generalized theory indicates that this technique can be extended to the removal of particles from a gas stream. The fundamental concept of HGMS is the interaction of the small paramagnetic particles with a ferromagnetic wire in a magnetic field of uniform background.[40] The ferromagnetic wire induces regions of highly nonuniform field intensity, exerting a net force on the particles and causing them to migrate to the surface of the wire, where they are retained. This process is analagous to enhanced filtration under a magnetic field except that the wire matrix is much more open.

In its most simple form, the HGMS system consists of a canister packed with fibers of a ferromagnetic material (steel wool), subjected to a strong external magnetic field (Figure 8-17). The resultant strong magnetic forces near the edges of the fibers provide very efficient collection of fine paramagnetic particles. The particles are removed from the gaseous stream as they pass through the canister. The fiber matrix eventually becomes fully loaded and must be cleaned. The overall particle collection efficiency is theoretically a function of the applied magnetic field, filter mesh parameters (fiber diameter and magnetization, packing density, and length of mesh in the direction of flow), particle parameters (diameter and magnetic susceptibility), and fluid parameters (viscosity and superficial velocity).[41]

Most of the applications of HGMS on a commercial scale have been in the kaolin clay industry, where it is used in the removal of weakly magnetic color bodies less than 2 μmA in diameter. Studies also have been made on fluid particle systems such as industrial waste process water from steel mills and electroplating operations, on nuclear reactor coolants, and on oils and hydraulic fluids. Potential has been demonstrated for application of HGMS to the desulfurization of coal.

Application of HGMS to particulate removal from gas streams has been studied only recently. A study was made on the particulate control of emissions from basic oxygen furnaces and electric arc furnaces used for steelmaking.[42] The collection efficiency in the experimental-scale study is summarized in Figure 8-18, which indicates that HGMS is effective in removing submicrometer particles of relatively high magnetic susceptibility from high-velocity gas streams. Several industrial processes in the iron and steel industry and the ferroalloy industry produce particulate emissions of sufficiently high magnetic susceptibility to make HGMS a potentially attractive control technique. The same investigators made a rough economic analysis of HGMS relative to the ESP and wet scrubber, as shown in Table 8-2. Although capital costs of HGMS are relatively high, it is a competitive process overall for highly efficient (greater than 99.9%) particulate matter removal.

More research is needed to define optimum conditions for operation of HGMS, along with a better understanding of the fundamental collection mechanisms. Both experimental and theoretical studies should be done for a variety of applications. Magnetic design, matrix size, and configuration should be specified for each application, as well as methods of cleaning the

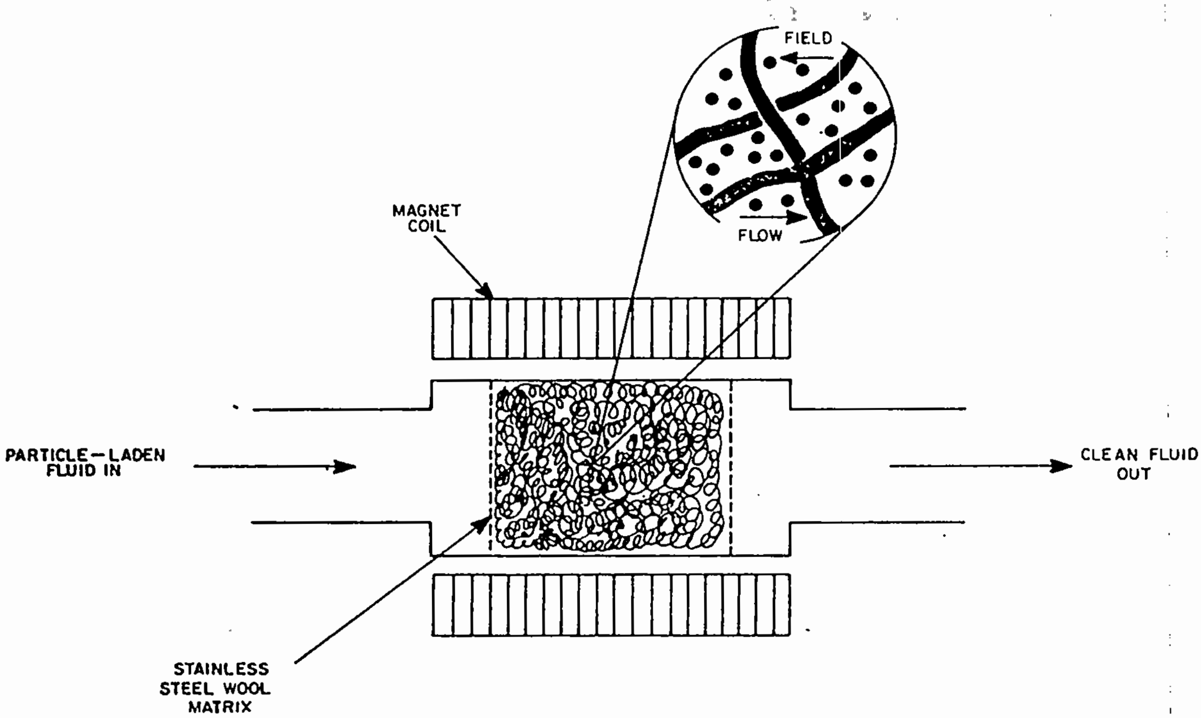


Figure 8-17. High gradient magnetic separator schematic representation.[47]

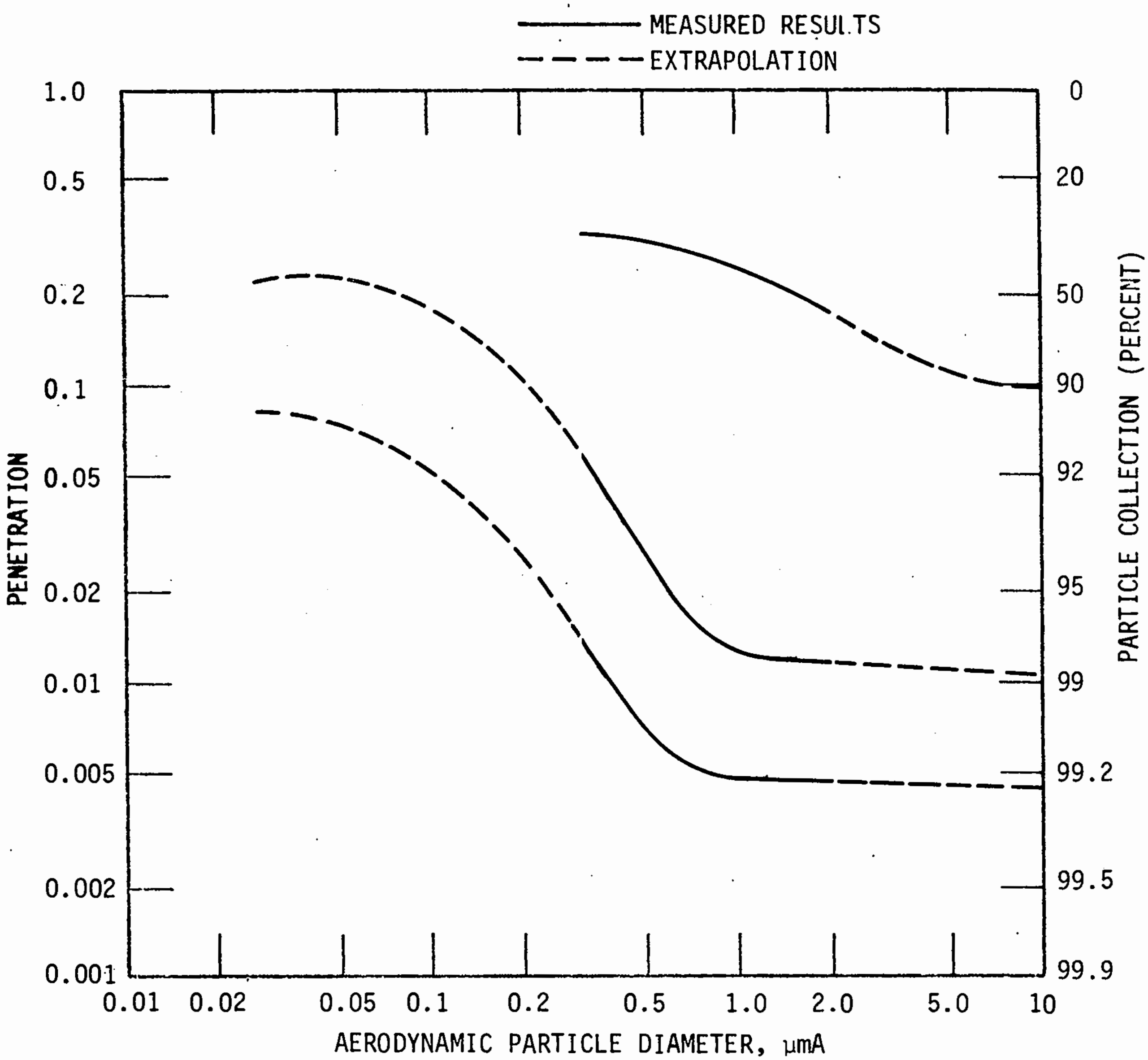


Figure 8-18. High-gradient magnetic separator fractional efficiency performance.[47]

TABLE 8-2. COMPARISON OF HIGH-GRADIENT MAGNETIC SEPARATOR AND CONVENTIONAL TECHNOLOGY

Device	ESP	Scrubber	HGMS
Collection efficiency, %	99.9	99.9	99.9
Flange-to-flange cost, \$ m^3/s	4042	2762	6653
\$ per cfm	1.91	1.30	3.14
Power requirement, kW per m^3/s	3.2	24.2	2.2
hp per 1000 cfm	2.0	15.3	1.4

[a]All estimates are referred to clean gas at 343°C, -1.5 kPa, 11 percent water by volume. Source, Ref. 39.

matrix when it is loaded with particles. It is reemphasized that for HGMS applications the particles must exhibit some paramagnetic behavior. As a consequence, this procedure is not widely applicable to many industrial gas streams. It is best suited for gas streams containing paramagnetic particles or particles that can be made paramagnetic by seeding with a magnetic material.

8.5 AGGLOMERATION TECHNIQUES

Particles in the submicron range are especially difficult to control by conventional methods. Techniques for increasing the size of submicron particles by agglomeration appear attractive because the larger particles could then be removed more effectively by conventional methods. Four such agglomeration techniques (thermal, turbulent, magnetic, and sonic) have been proposed. Of these, the sonic appears the most promising and the most advanced in experimental and industrial demonstrations. Magnetic agglomeration techniques offer potential to enhance collection, although application is limited to process emissions with ferromagnetic particles. Thermal and turbulent agglomeration techniques have been evaluated,[43,44] but are not discussed because of their limited potential for future development.

8.5.1 Sonic Agglomeration

Sonic agglomeration techniques have been researched for many years, the observation that particles behave differently under the influence of sound waves being made in 1931. The mechanisms of agglomeration are complex and not well understood; as many as nine possible mechanisms have been postulated.

The acoustic field affects the hydrodynamic forces and vibrational movements of the particles within the flow field and thus accelerates collisions between particles. Reference 45 presents a thorough discussion of the pathways involved. Some of the theoretical and experimental analyses allow the following conclusions regarding sonic particle agglomeration:[46]

1. The optimum frequency for agglomerating fine particles (2 μmA and less) is approximately 10 kHz. Particles larger than 2 μmA serve as collecting centers, and the agglomeration rate is directly proportional to the number of such collection centers.

2. Highly polydispersed aerosols are easier to agglomerate than monodispersed aerosols (i.e., if particles are all of nearly the same size, acoustic agglomeration is not effective).

3. Acoustic agglomeration rates vary in proportion to the square root of the acoustic intensity.

4. Physical properties of aerosol particles have comparatively little effect on acoustic agglomeration.

5. Residence times for significant agglomeration are about 5 to 10 s.

6. Sound intensities of about 160 dB are required for effective industrial applications.

7. Water sprays can enhance sonic agglomeration.

Table 8-3 shows some results of industrial tests with sonic agglomeration (used in conjunction with other mechanical collection devices).[47]

The requirement of 160 dB sound intensities for sonic agglomeration can be translated into a power requirement of about 1.6 kW per m^3/s, which is equivalent to about 750 kW for a modern pulverized coal-firing utility station (470 m^3/s volume flowrate.) Also, the intense sound levels create noise that must be muffled. Recent studies indicate possibilities of lowering the sound intensity requirements.[48] Analysis also suggests that resonating chambers producing standing waves could reduce the energy requirements.[51] Thus, acoustic agglomeration is considered to be the most promising of the agglomeration methods for treating industrial gases.

Table 8-3. RESULTS OF INDUSTRIAL TESTS WITH SONIC AGGLOMERATION

Aerosol	Aerosol and gas stream properties				Agglomeration chamber					Collector system		
	Particle radius, μmA	Concentration by weight, g/m³	Temperature °C	Volume treated, m³/h	Type and dimensions, m	Type of siren	Frequency, kc/s	Intensity, W/cm²	Length of sonic treatment, s	Type	Amount removed without sound, %	Amount removed without sound, %
Zinc oxide sublimate from roasting zinc ore	0.5-5.0 predominant 2.5	1.2	40-100	1600	Experimental, reverse flow 0.75 dia. x 10	Dynamic axial	3-3.5	0.1	10	Cyclone	84-87	94-98
Zinc oxide sublimate from copper smelting	0.5-4.0	0.5-20	50-350	1300-2160	The same, 1.0 dia. x 9	Dynamic, radial	3-9	0.13	10	Cyclone 1.35 m dia.	70	90-95
Zinc oxide sublimate from brass melting	0.4-0.6,	10	400	7000	The same, 0.7 dia. x 10	Dynamic, axial	0.7	0.6	2.5	Cyclone 0.15-0.3 m and filters (in series)		99.8
Coke gas (tar)	0.5-5.0, predominant 2.5	30-70	40-60	1300-2100	The same, 0.5-0.64 dia. x 9	The same	4	0.1	5-8.5	Two cyclones (in parallel)	88	99-99.8
Cracking gas (condensate)	0.5-5.0	5-70	35	1200	The same, 0.5 dia. x 9	The same	4	0.1	5	The same	76-82	97.5-99.3
Cracking (condensate)	0.5-5.0 predominant 3.0-3.5	6-15	40	12,000	Industrial, reverse flow 1.6 dia. x 11 (2 sets)	The same	3.5	0.1	6	Two Pelouze tar extractors (in parallel)	73	95
Open-hearth furnace smoke	2.5 (55%)	2	150	5000	Experimental, reverse flow, with water addition	Dynamic	2.2			Wet type roctoclone	45	90.7

(continued)

Table 8-3 (continued)

Aerosol	Aerosol and gas stream properties				Agglomeration chamber					Collector system		
	Particle radius, μmA	Concentration by weight, g/m³	Temperature °C	Volume treated, m³/h	Type and dimensions, m	Type of siren	Frequency, kc/s	Intensity, W/cm²	Length of sonic treatment, s	Type	Amount removed without sound, %	Amount removed without sound, %
Carbide furnace smoke	0.2-15, predominant 0.5	0.25-2.8	20	5000	Experimental, reverse flow	Static	7-10		4-6	Multicyclones (in parallel	11	94
Carbide furance smoke	The same	0.25-2.8	120	500	The same, with water addition (5 g/m³)	Static	10.5		4-6	The same		86
Gas furnace black	0.03-0.07	1.2-12.6	40	1700-2000	Experimental, direct flow 1.1 dia. x 6.6	Dynamic, radial	4	0.5-1.0	4.5	Two cyclones 1.3 in dia. (in series)	40	83-90
Gas furnace black	0.03-0.07	1.2-2.1	40	1700-2000	The same, with water addition	The same	2-4	0.5-1.0	1.2	The same	8-32	99
Aggregated gas black	0.5-15	0.5-2.5		600	Experimental, reverse flow with water 0.5 dia.	Dynamic, axial	3	0.1	10	One or four cyclones (in parallel)	68-72	95
Atomized carbon black	0.1-0.2	26	82	45	Experimental, rising steam -0.29 dia. x 1.9	Static with pump-off	4.6	1.0	7	Two cyclones and a glass cloth filter (in series)	(30)[a]	99-98 (97)[a]
Hard coal black	0.5-1.0	0.5.2.4	80-90	90-100	Experimental, reverse flow, 0.2 dia. x 2.5	Dynamic, axial	3.6	0.10-0.14	3-4	Cyclone 0.15 dia.	68-74 (81)[b]	87 (97)[b]

(continued)

Table 8-3 (continued)

	Aerosol and gas stream properties				Agglomeration chamber					Collector system		
Aerosol	Particle radius, μmA	Concentration by weight, g/m³	Temperature °C	Volume treated, m³/h	Type and dimensions, m	Type of siren	Frequency, kc/s	Intensity W/cm²	Length of sonic treatment, s	Type	Amount removed without sound, %	Amount removed without sound, %
Sulfuric acid fog	0.5-5.0	5-40	180	1700	The same, 0.6 dia. x 6	The same	2.15	0.1	3	Multicy-clones (in parallel)	84	99.6-99.9
Natural sulfuric acid fog	0.25-2.5	1	50	40,000	Industrial, composite flow, 2.4 dia. x 10.5 (2 sets)	Dynamic, radial	2.25	0.1	4	Two cy-clones (in parallel)		90
Dilute sulfuric acid fog	2.5-50, predominant 7.5	0.5-1.2	20	1800	Experimental, reverse flow, 0.64 dia. x 11	Dynamic, aerial	1-2	0.1	7	Four cy-clones (in parallel)	69-72	78-82

[a] Result without cloth filter, in parentheses.
[b] Result from water addition, in parentheses.

The emergence of new energy-producing technologies may also necessitate the use of novel particulate separation methods such as sonic agglomeration. Sonic agglomeration in conjunction with a mechanical separator (cyclone) may be effective under these conditions, and studies are being performed.[49]

8.5.2 Magnetic Agglomeration

Magnetic fields can alter the motion of particles suspended in a gas stream, depending on the magnetic permeability of the particles.[50] By adjustment of the strength of the magnetic fields to accommodate the nature of the particles and the flow field, particle agglomeration may be enhanced. Magnetic agglomeration will work best with ferromagnetic particles, although theoretically it should also be effective with charged particles or particles having permanent or induced dipole moments.

Applications to industrial gas cleaning are limited because long residence times and strong magnetic fields are needed even with ferromagnetic materials, and most particulate emissions are not ferromagnetic. Direct capture of submicrometer particles under high-gradient magnetic fiels may be more promising; this concept is discussed in further detail in a preceding section.

REFERENCES

1. Kearns, M. T., et al. Union Carbide's High Intensity Ionizer Applied to Enhance a Venturi Scrubber System. In: Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. 3, Denver, Colorado. pp. 73-84. EPA-600/7-79-044c. February 1979.

2. Lear, C. W. Charged Droplet Scrubber for Fine Particle Control: Laboratory Study. EPA-600/2-76-249a. September 1976.

3. Krieve, W. F., and J. M. Bell. Charged Droplet Scrubber for Fine Particle Control: Pilot Demonstration. EPA-600/2-76-249b. September 1976.

4. Pilot, M. J., and D. F. Meyer. University of Washington Electrostatic Spray Scrubber Evaluation. EPA-600/2-76-100. April 1976.

5. Cooper, D. W., et al. Evaluation of Eight Novel Fine Particle Collection Devices. EPA-600/2-76-035. 1976.

6. Pilot, M. J., and G. A. Raemhild. University of Washington Electrostatic Scrubber Tests at a Coal Fired Power Plant. EPA-600/7-78-177b. December 1978.

7. McCain, J. D., and W. B. Smith. Lone Star Steel Steam-Hydro Air Cleaning System Evaluation. EPA-650/2-74-028. April 1974.

8. McCain, J. D. Evaluation of Aeronetics Two-Phase Jet Scrubber. EPA-650/2-74-129. December 1974.

9. Calvert, S., et al. Feasibility of Flux Force/Condensation Scrubbing for Fine Particulate Collection. EPA-650/2-73-036. October 1973.

10. Calvert, S., and S. Gandhi. Fine Particle Collection by a Flux Force/Condensation Scrubber: Pilot Demonstration. EPA-600/2-77-238. December 1977.

11. Yung, S., C. R. Chmielewski, and S. Calvert. Mobile Bed Flux Force/Condensation Scrubbers. EPA-600/7-79-071. February 1979.

12. Lausen, P., H. Henrikson, and H. H. Peterson. Energy Conserving Pulse Energization of Precipitators. In: Second Symposium on the Transfer and Utilization of Particulate Control Technology. (EPA publication pending.) 1980.

13. Belco Pollution Control Corporation. Technical Description of the Belco Pulsed Power Supply. CPA 22-69-143. March 18, 1970.

14. Feldman, P.C., and H.I. Milde. Pulsed Energization for Enhanced Electrostatic Precipitation in High-Resistivity Applications. In: Symposium on the Transfer and Utilization of Particulate Control Technology. pp. 253-274. EPA-600/7-79-044a.

15. Penney, G.W., and P.C. Gelfand. The Trielectrode Electrostatic Precipitator for Collecting High-Resistivity Dusts. APCA Journal, Vol. 28, No. 1. pp. 53-55. January 1978.

16. Masuda, S., et al. Bias-Controlled Pulse Charging System for Electrostatic Precipitator. pp. 241-251. EPA-600/7-79-044a.

17. Ito, R., and K. Takimota. Wide Spacing E. P. is Available in Cleaning Exhaust Gases from Industrial Sources. pp. 297-305. EPA-600/7-79-044a.

18. Ito, S., et al. Roof-Mounted Electrostatic Precipitator. pp. 485-495. EPA-600/7-79-044a.

19. Pontuis, D.H., D.V. Buhs, and L.E. Sparks. Field Evaluation of a Two-Stage ESP for High-Resistivity Dusts. (To be published in Staub journal.) 1980.

20. White, H.J. Industrial Electrostatic Precipitation. Addison-Wesley Publishing Company, Reading, Massachusetts. 1963.

21. Dismukes, E.B., and J. P. Gooch. Fly Ash Conditioning with Sulfur Trioxide. EPA-600/2-77-242. December 1977.

22. Patterson, R., et al. Flue Gas Conditioning Effects on Electrostatic Precipitators. In: Symposium on the Transfer and Utilization of Particulate Control Technology, Vol. I. Denver, Colorado. pp. 169-177. PB 295, 226. EPA-600/7-79-044a. February 1979.

23. Bubenick, D.V. Economic Comparison of Selected Scenarios for Electrostatic Precipitators and Fabric Filters. In: Section 14 Power Generation 1. Emission Control. Presented at the 70th Annual Meeting of APCA. Toronto, Ontario, Canada. June 1977.

24. Atkins, R.S., and D.V, Bubenick. Keeping Fly Ash Out of the Stack. Environmental Science and Technology. p. 657. June 1978.

25. Harrison, M.E. Economic Evaluation of Precipitator and Baghouse for Typical Power Plant Burning Low Sulfur Coal. Presented at the American Power Conference. Chicago, Illinois. April 24-27, 1978.

26. Breisch, E.W. Method and Cost Analysis of Alternative Collectors for Low Sulfur Coal Fly Ash. pp. 121-129. EPA-600/7-79-044a.

27. Petersen, H.H. Conditioning of Dust with Water-Soluble Alkali Compounds. pp. 99-111. EPA-600/7-79-044a.

28. Lederman, P.B., et al. Chemical Conditioning of Fly Ash for Hot-Side Precipitation. pp. 79-98. EPA-600/7-79-044a.

29. Bush, J.R., P.C. Feldman, and M. Robinson. Development of a High Temperature/High Pressure Electrostatic Precipitator. EPA-600/7-77-132. November 1977.

30. Helfrich, D.J., and T. Arimai. Electrostatic Filtration and the Apitron/Design and Field Performance. In: Novel Concepts, Methods and Advaned Technology in Particulate Gas Separation. (T. Arimai, ed.).

31. Harmon, D.L. Electrostatically Augmented Particulate Collection Devices. In: Proceedings of the First Workshop of Particulate Control. Kernforschungsanlage Julich Gmbh. March 1978.

32. Reid, D.L., and L.M. Browne. Electrostatic Capture of Fine Particles in Fiber Beds. EPA-600/12-76-132. May 1976.

33. Yung, S.C., et al. Granular Bed Filter for Particulate Collection at High Temperature and Pressure. Air Pollution Technology, Inc. Presented at EPA/DOE Symposium on High Temperature, High Pressure Particulate Control. Washington, D.C. September 1977.

34. Hoke, R.C., and M.W. Gregory. Evaluation of a Granular Bed Filter for Particulate Control in Fluidized Bed Combustion. Exxon Research and Engineering Company. Presented at EPA/DOE Symposium on High Temperature, High Pressure Particulate Control. Washington, D.C. September 1977.

35. Wade, G.L. Performance and Modeling of Moving Granular Bed Filters. Combustion Power Company, Inc. Presented at EPA/DOE Symposium on High Temperature, High Pressure Particulate Control. Washington, D.C. September 1977.

36. Calvert, S., and R. Parker. Effects of Temperature and Pressure on Particle Collection Mechanisms: Theoretical Review. EPA-600/7-77-002. January 1977.

37. Shackleton, M.A. High Temperature, High Pressure Particulate Control with Ceramic Bag Filters. EPA-600/7-78-194. October 1978.

38. Drehmel, D.C., and D.F. Cilikerti. High Temperature Fine Particle Control Using Ceramic Filters. Presented at EPA/DOE Symposium on High Temperature, High Pressure Particulate Control. Washington, D.C. September 1977.

39. Gooding, C.H., T.W. Sigmon, and L.K. Monteith. Application of High Gradient Magnetic Separation to Fine Particle Control. EPA-600/2-77-230. 1977.

40. Cummings, D.L., et al. Capture of Small Paramagnetic Particles by Magnetic Forces from Low Speed Fluid Flows. AIChE Journal. 22:(569). 1976.

41. Luborsky, R.E., and B.J. Drummond. High Gradient Magnetic Separation: Theory vs. Experiment. IEEE Transactions or Magnetics. 2:(1696). 1975.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-450/3-81-005a	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Control Techniques for Particulate Emissions From Stationary Sources - Volume 1		5. REPORT DATE September 1982 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Environmental Protection Agency Office of Air Quality Planning and Standards Research Triangle Park, North Carolina 27711		10. PROGRAM ELEMENT NO. 3450-12 11. CONTRACT/GRANT NO. 68-02-3173 (Task No. 12) PEDCo Environmental, Inc.
12. SPONSORING AGENCY NAME AND ADDRESS DAA for Air Quality Planning and Standards Office of Air, Noise, and Radiation U.S. Environmental Protection Agency Research Triangle Park, North Carolina 27711		13. TYPE OF REPORT AND PERIOD COVERED Final 14. SPONSORING AGENCY CODE EPA 200/04

15. SUPPLEMENTARY NOTES

This document is issued per the requirements of Section 108 of the Clean Air Act Amendments of 1977.

16. ABSTRACT

Control Techniques for Particulate Emissions from Stationary Sources Volumes 1 and 2 present recent developments of control techniques which have become available since preparation of an earlier document entitled Control Techniques for Particulate Air Pollutants (AP-51).

Volume 1 of this document presents available data on characterization; sampling methods and analytical techniques for particulate emissions; particle behavior and characteristics; types of particulate control systems, their operating principles, design, operation, and maintenance; costs and environmental consideration of particulate control techniques; and emerging technologies for particulate removal systems. A major portion of Volume 1 presents information to quantify particulate removal efficiencies by particulate size for the differing types of particulate removal systems.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Particulates Control Techniques Costs Emission Control Operation and Maintenance Design		13B
18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 460
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

*U.S. GOVERNMENT PRINTING OFFICE: 1982--539-001/3003

United States
Environmental Protection
Agency

Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park NC 27711

Official Business
Penalty for Private Use
$300

Publication No. EPA-450/3-81-005a

Postage and
Fees Paid
Environmental
Protection
Agency
EPA 335

U.S. MAIL

If your address is incorrect, please change on the above label, tear off, and return to the above address.
If you do not desire to continue receiving this technical report series, CHECK HERE ☐; tear off label, and return it to the above address.